ECEN689: Special Topics in Optical Interconnects Circuits and Systems Spring 2022

Lecture 13: Automatic Monitor-Based Microwave Photonic Systems

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Announcements

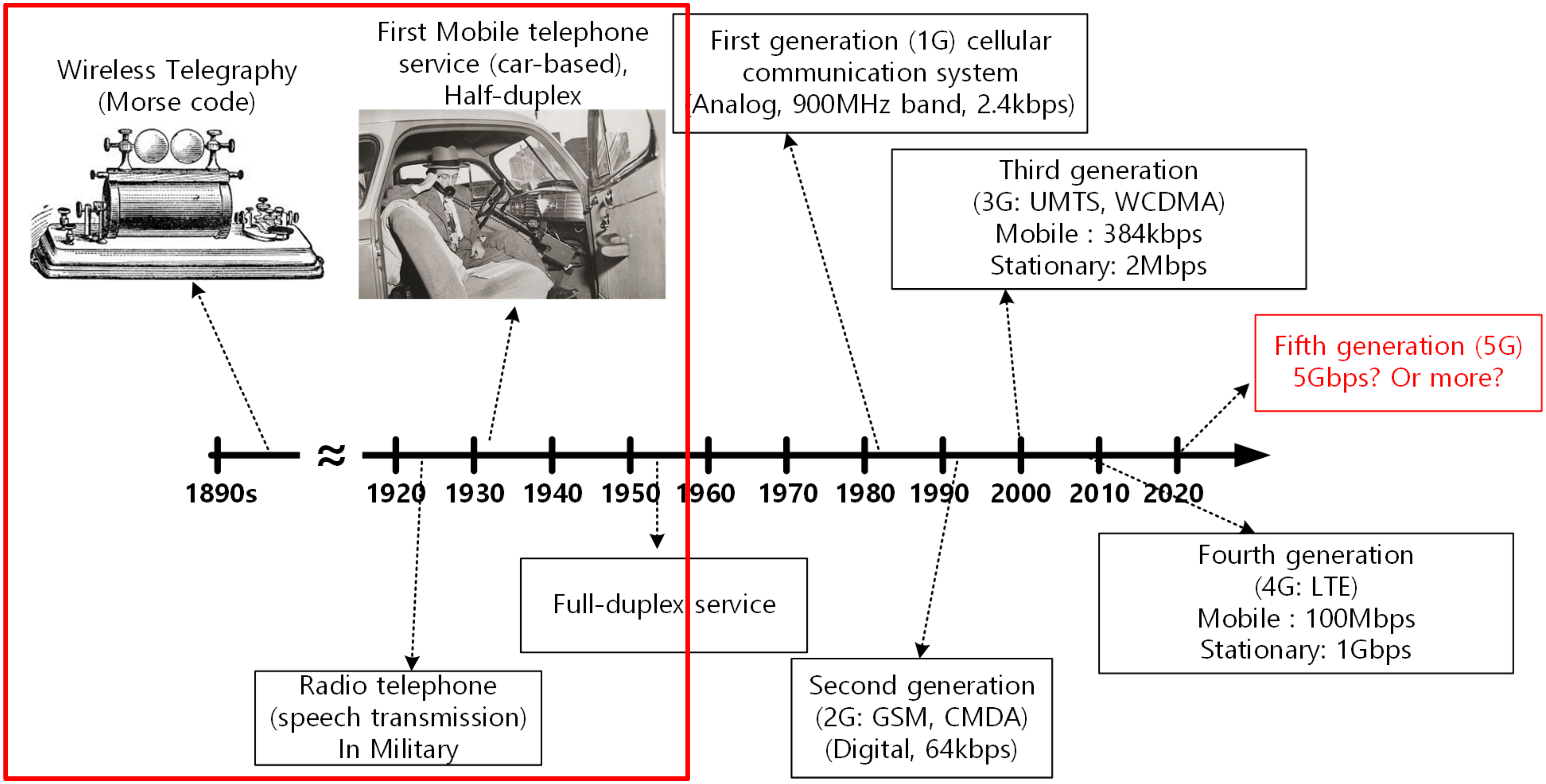
- Exam 2 is on Apr. 28
  - In class
  - One double-sided 8.5x11 notes page allowed
  - Bring your calculator
  - Covers through Lecture 12

- Project Report Due May 3

Outline

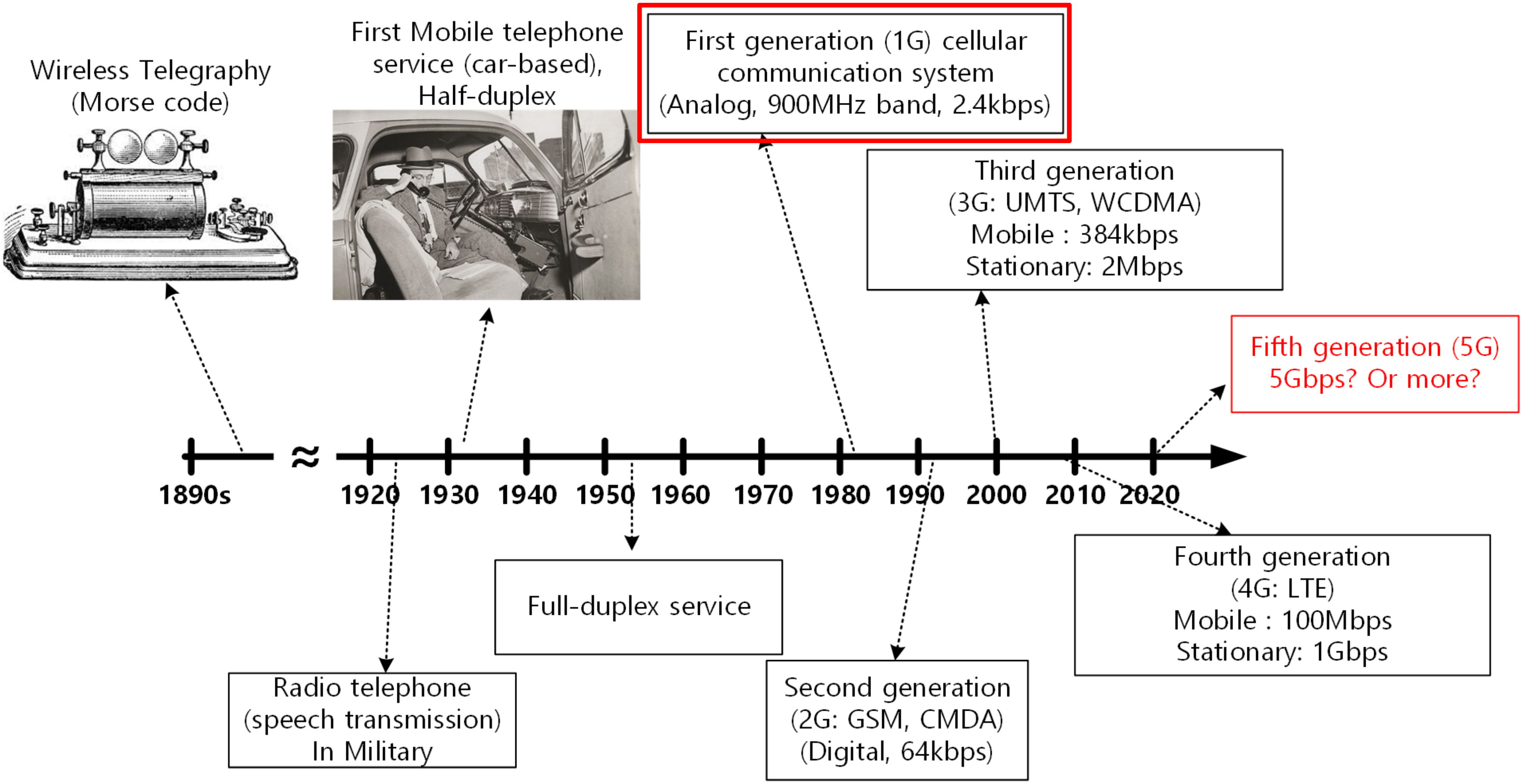
- Motivation
- Monitor-Based Tuning Principles
- Automatic Filter Tuning
- Automatic Optical Beamforming Network Tuning
- Conclusion

Development of Wireless Communication



First Wireless communication (1890s) : Telegraphy
First speech transmission (1920s) : Military between naval ships
First Mobile telephone service (1930s) : Taxi <-> Telephone exchange office

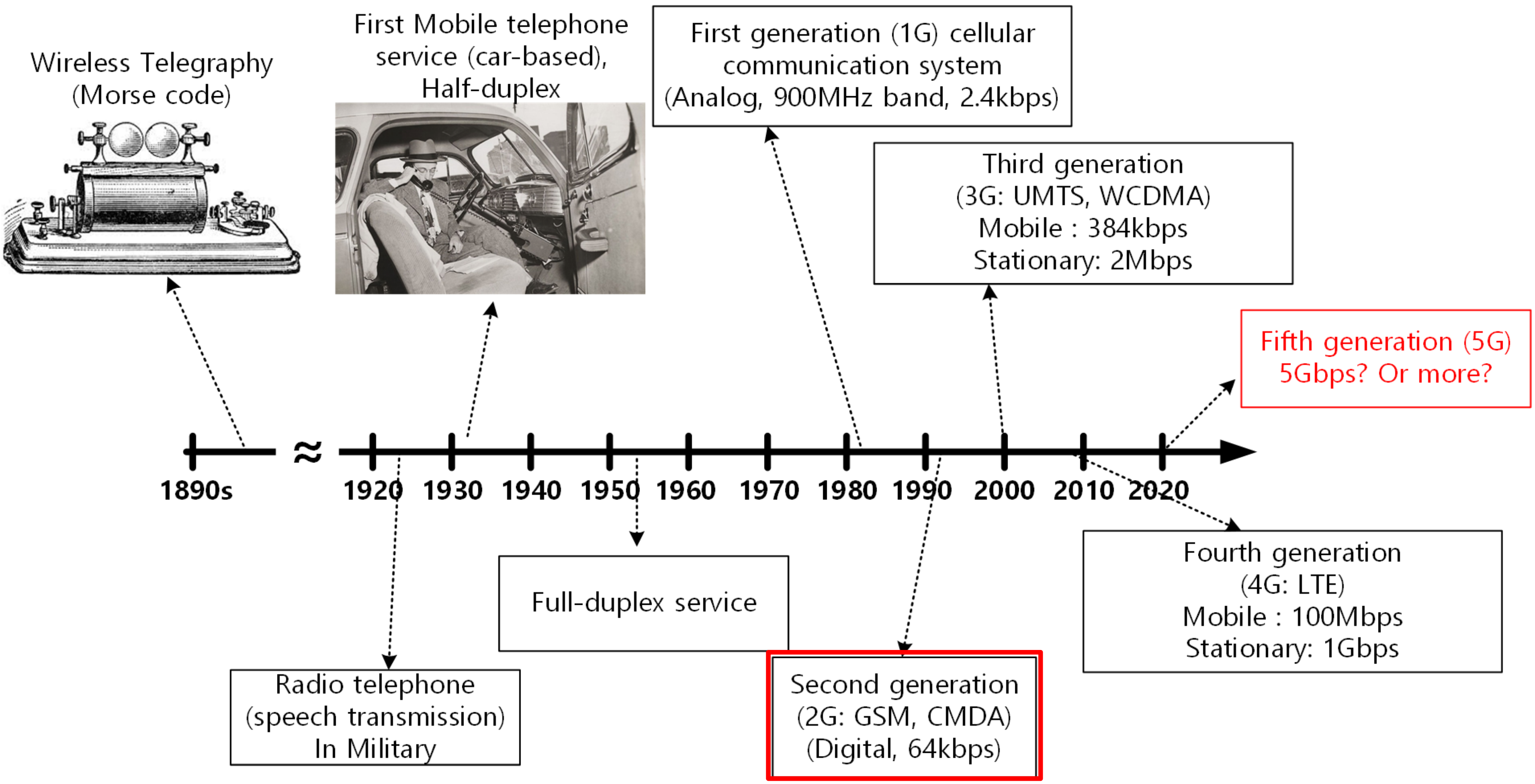
Wireless Communication (1G)



First cellular communication system (1G) : Analog signal, Analog systems

- (-) Poor voice quality, Poor battery life, Large phone size, Limited Capacity

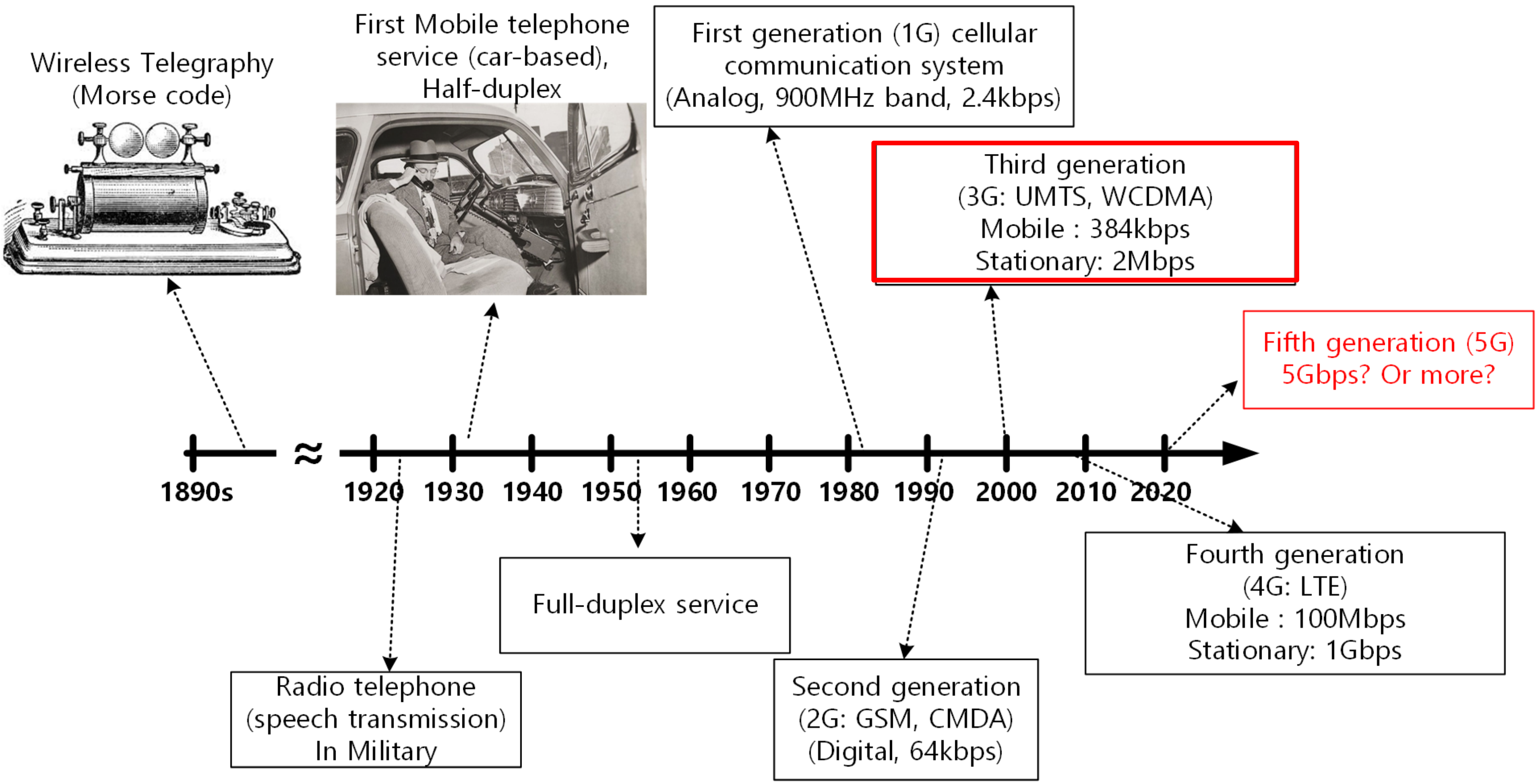
Wireless Communication (2G)



Second cellular communication system (2G) : Digital signal, Digital systems

- Digital Systems, Ability to send SMS, Voice encrypted
- (-) Low data-rate (64kbps)

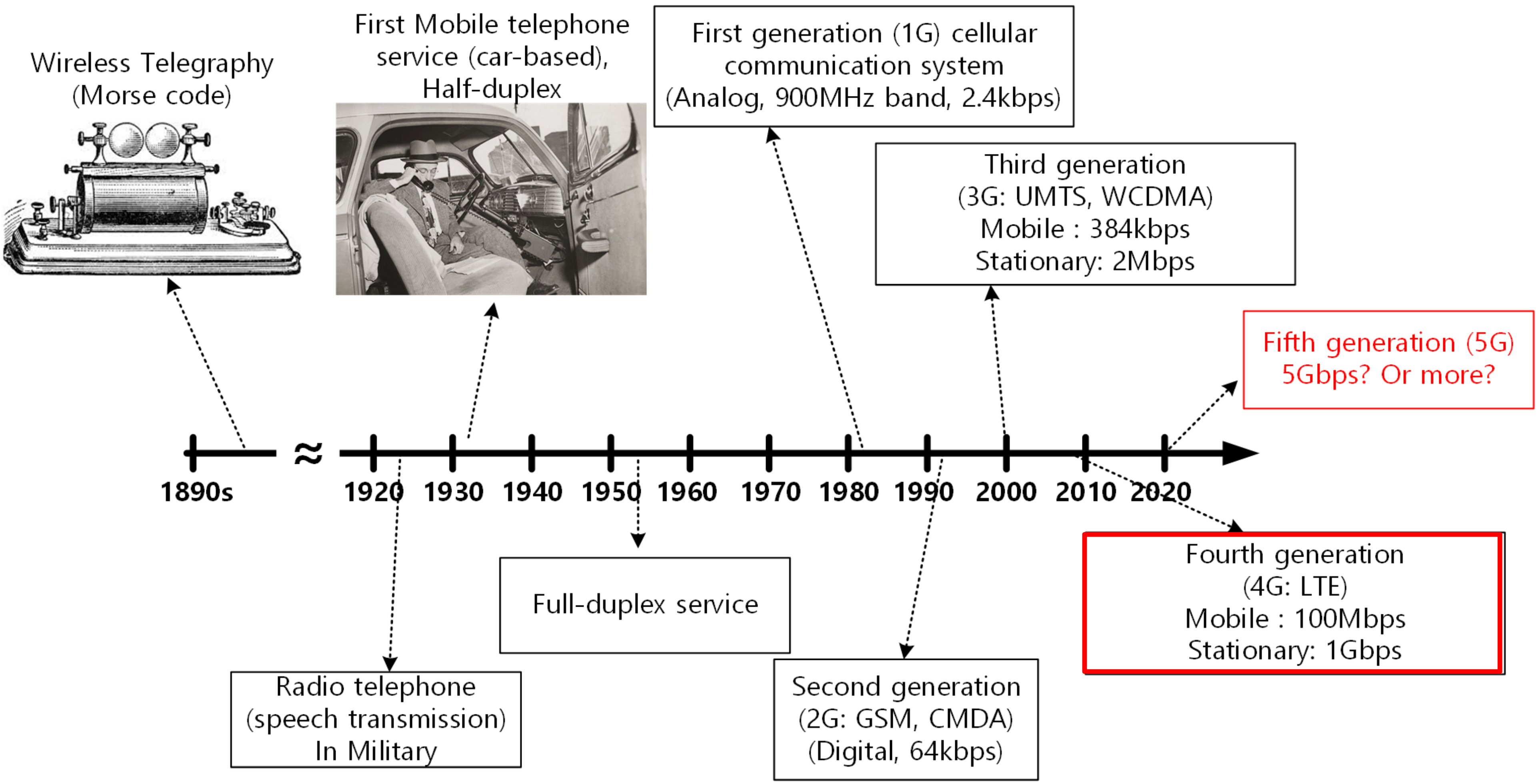
Wireless Communication (3G)



Third cellular communication system (3G) : Large capacities, Broadband

- Send/Receive large email messages, Internet access, TV streaming

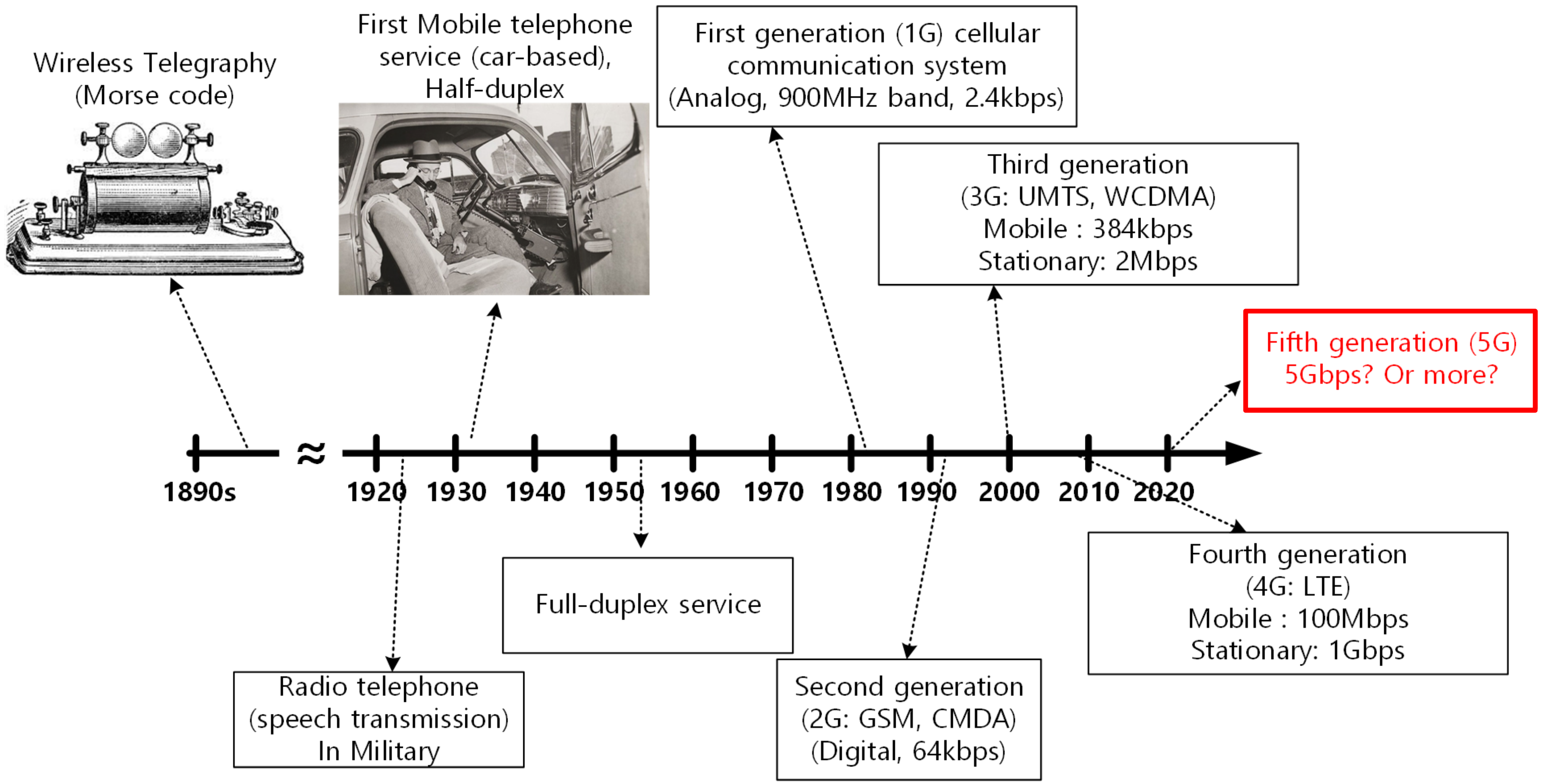
Wireless Communication (4G)



Fourth cellular communication system (4G)

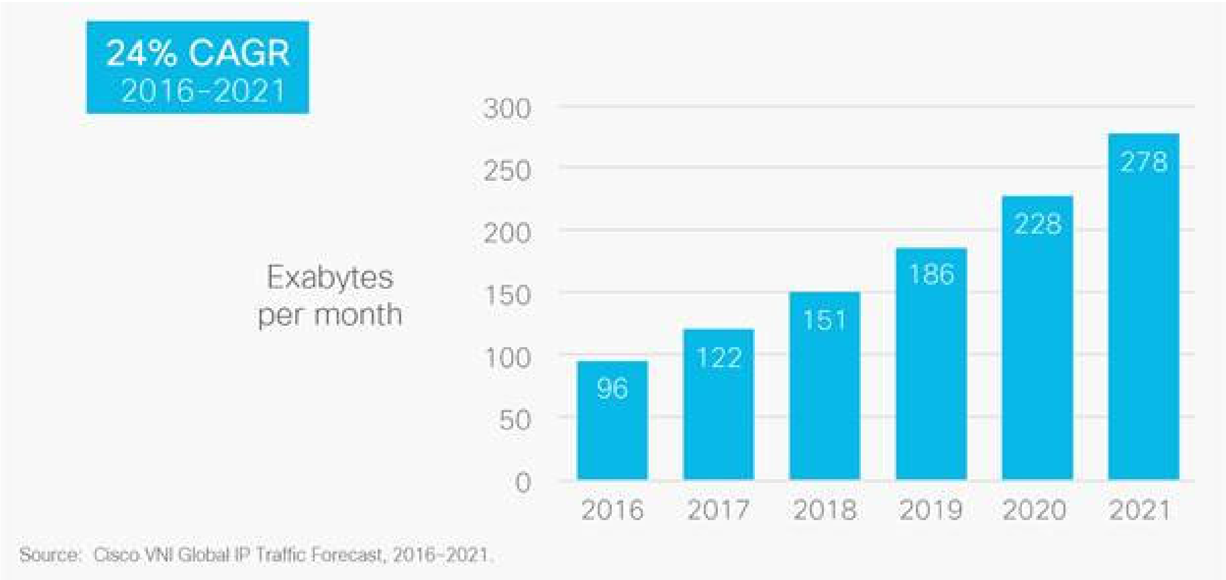
- Higher data rates and expanded multimedia services

Wireless Communication (5G)



Fifth cellular communication system (5G)

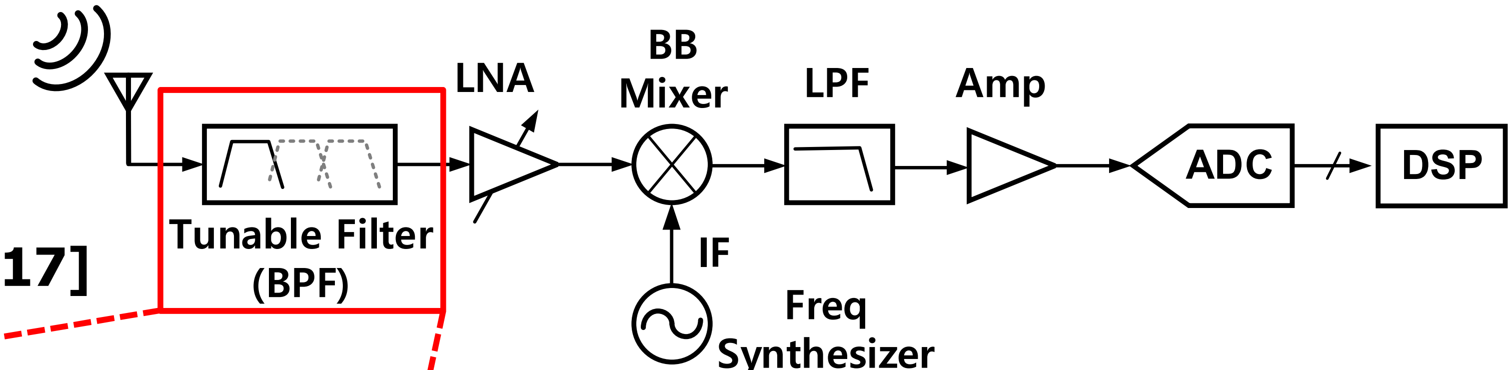
Development of Wireless Communication



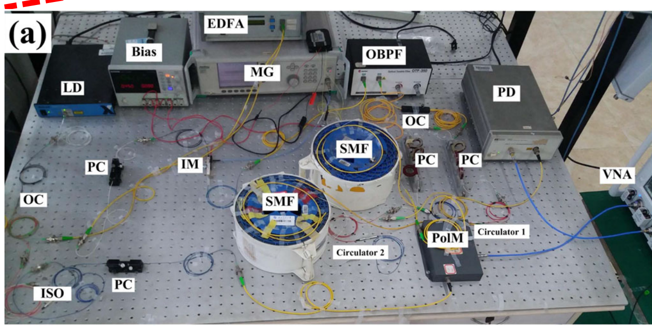
[Cisco Visual Networking Index ,2016]

- Continuously Increasing data traffic
- Fifth cellular communication system (5G)
  - Still no consensus on frequency bands, architecture of network.
  - To meet future data traffic technology evolution is required
    - Reducing the cell size (higher Integration)
    - Building massive multiple-input/output system (MIMO)
    - Shifting to higher frequency bands for wider amount of spectrum
- Challenging to meet with existing electrical systems

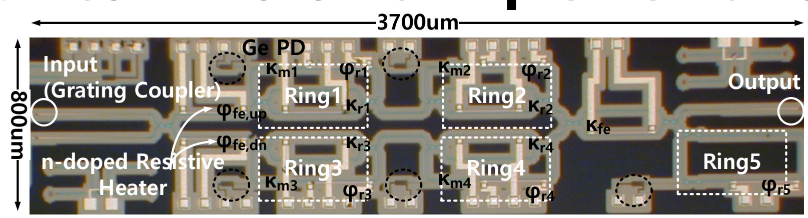
Microwave Photonics



[Li MTT 2017]



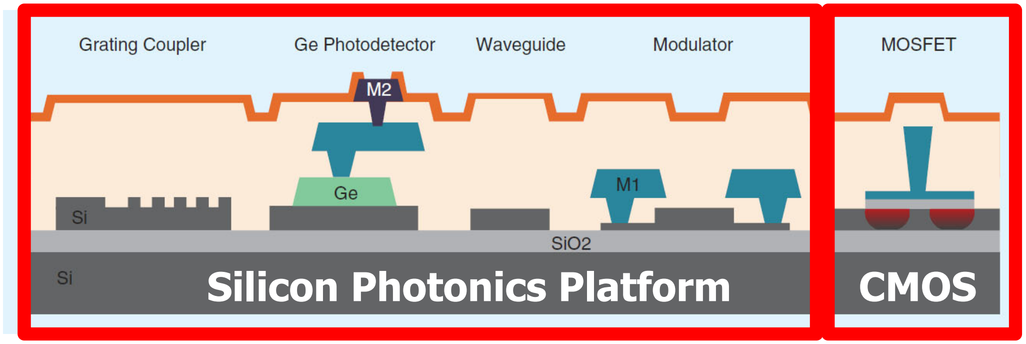
Silicon Photonic Implementation



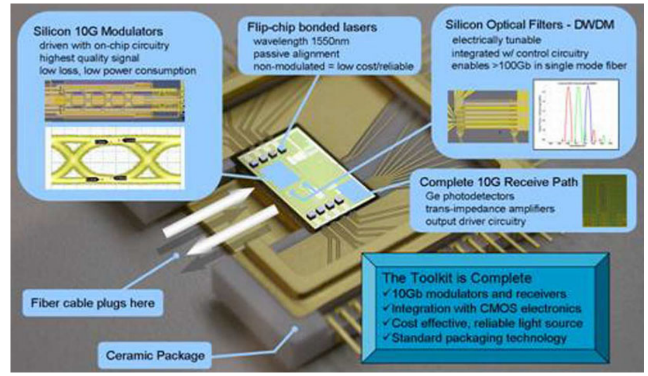
[Choo JLT 2018]

- Advantages
  - Operating at optical frequencies offers extremely high bandwidth
  - Low-loss transmission is possible over optical fibers
  - Orders of magnitude improvement in frequency tuning
- Traditionally systems implemented with bulky discrete components
- Silicon photonic implementations offers significant size, weight, and power improvements

Silicon Photonics



[M. Hochberg, *IEEE Solid-State Circuits Mag*, 2013]

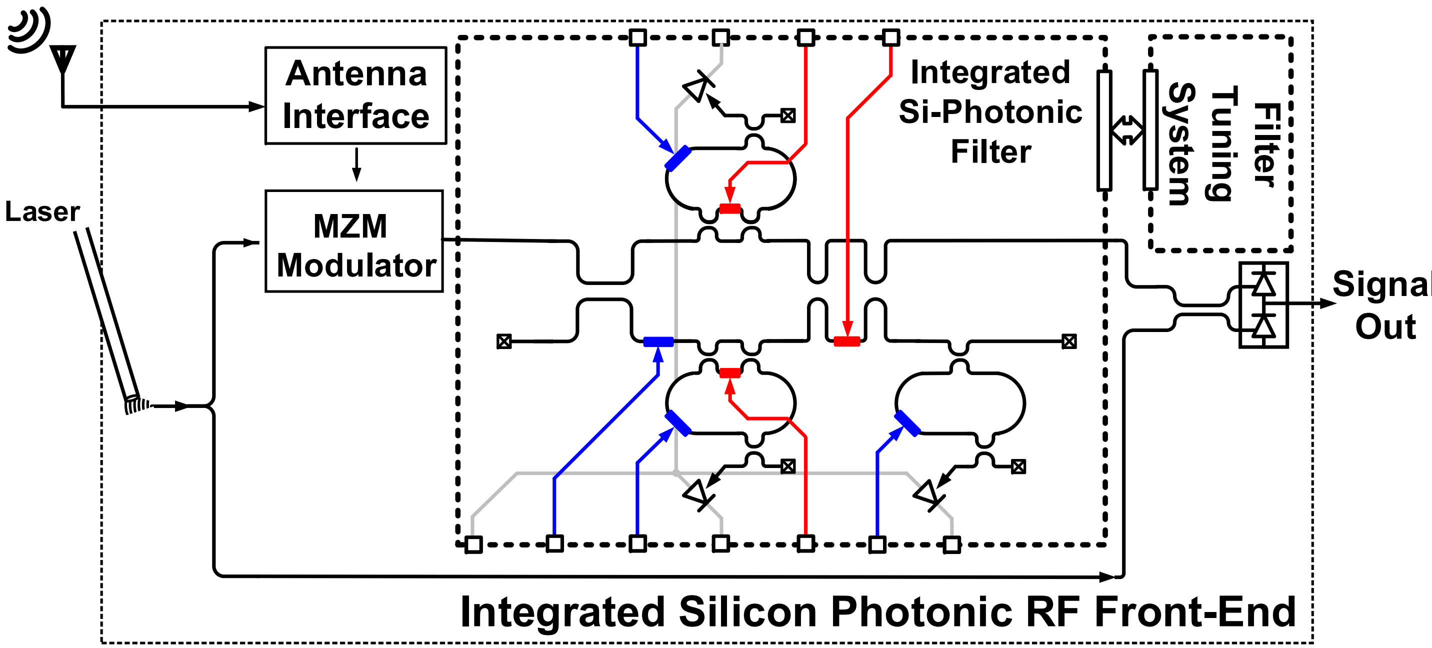


[C. Gunn, *IEEE Micro*, 2006]

- Motivation for Silicon Photonics[1] (SiP)
  - Availability of high-quality SOI wafer
    - High index contrast between Silicon and SiO_2 offers strong optical confinement
    - Ideal platform for planar waveguide circuits
- Compatibility with the mature silicon IC manufacturing
    - Reuse of mature CMOS fabrication infrastructure
    - Monolithic integration with CMOS chips
- Emergence of Silicon photonic integrated circuits made RF photonics promising candidates for the future wireless communication systems[2]

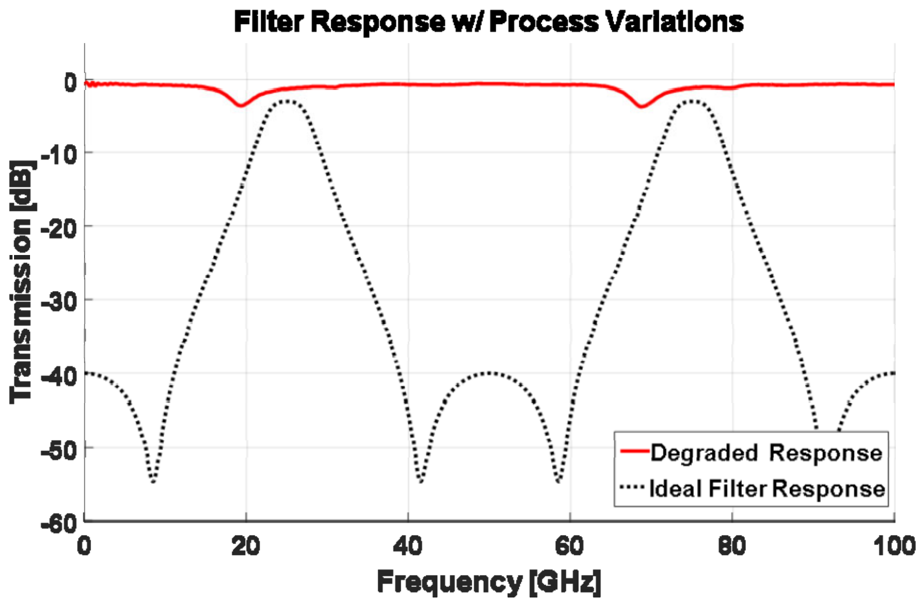
[1] A. Safarian, RFIC symposium, 2007
[2] Y. Wu, IEEE TCAS II, 2003

Silicon Photonic mm-Wave Front-End



- Silicon photonic platforms offer the ability to integrate many photonic circuits on a single die
- Micro/mm-wave photonic filters are promising candidate for future wideband receivers since they can support wide bandwidth and dynamic filtering over a broad spectral range

Si-Photonic Filters w/ Process Variations



- Photonic devices are sensitive to process and temperature variations
  - Filter responses degrade significantly due to process variations
  - Center frequency shifts with temperature variations
- Manual calibration with spectrum analyzer is expensive, time consuming, and prone to human errors
- Need precise automatic calibration solution

Outline

- Motivation
- Monitor-Based Tuning Principles
- Automatic Filter Tuning
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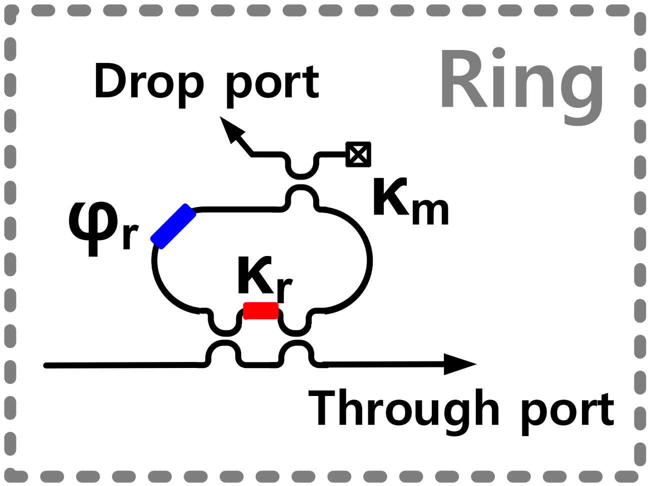
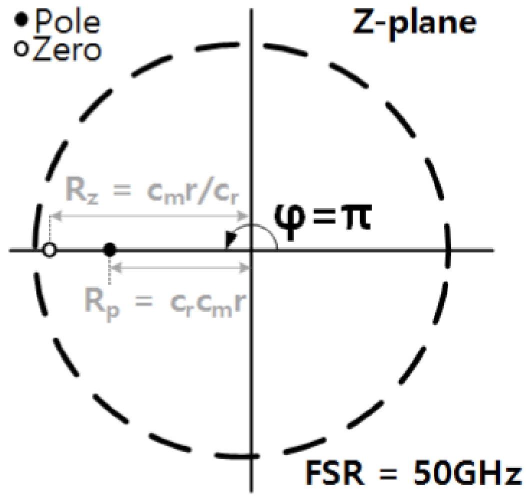
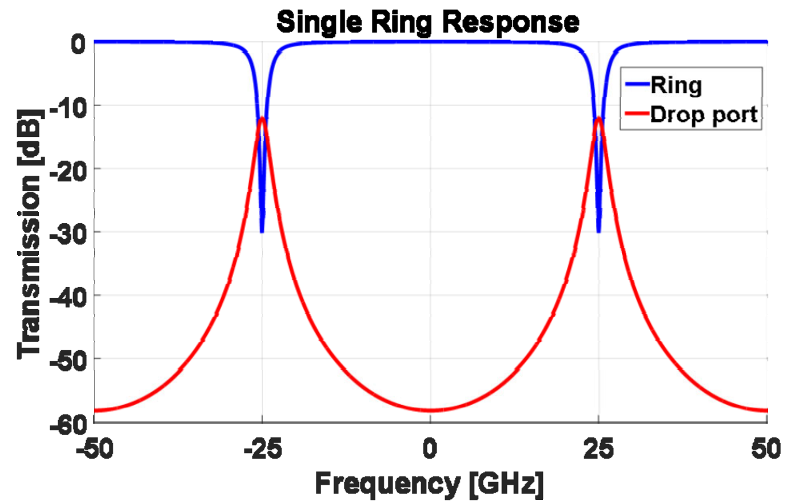
Ring Resonator Response





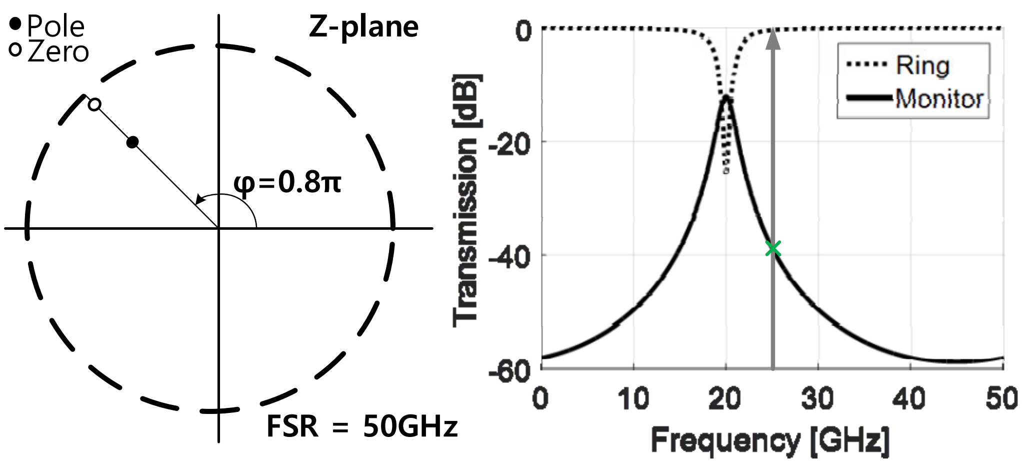


$$H_{through}(z) = \frac{c_r - c_m r e^{j\varphi_r} z^{-1}}{1 - c_m c_r r e^{j\varphi_r} z^{-1}}, \quad H_{drop}(z) = \frac{s_m c_r r e^{j\varphi_r} z^{-1}}{1 - c_m c_r r e^{j\varphi_r} z^{-1}}, \quad \text{where } c = \sqrt{1-\kappa},\ s = \sqrt{\kappa}$$

- Ring's through and drop port responses are complementary with the notches and peaks in alignment

Monitor-Based Tuning (Resonance)

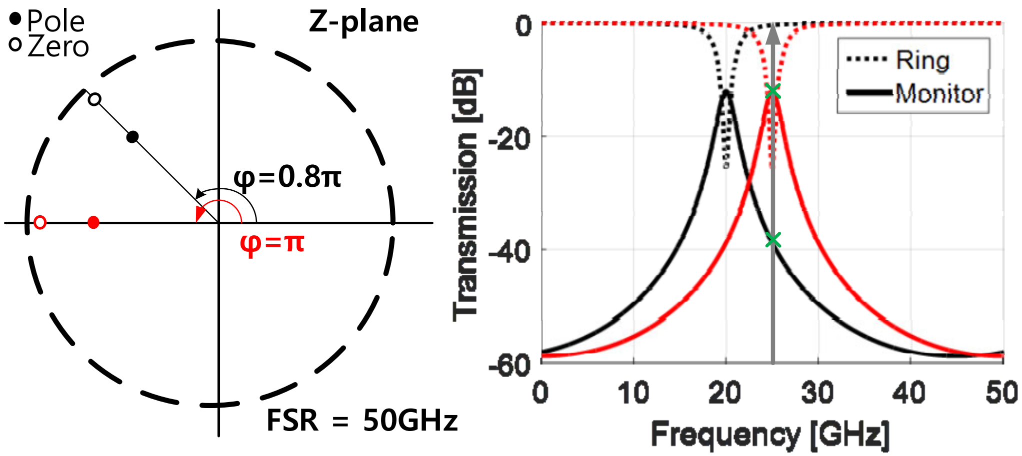
Resonance tuning



- Resonance tuning(φ_r)
  - Ring phase shifter shifts ORR’s resonance frequency
  - Resonance is tuned to frequency stimulus by maximizing monitor reading

Monitor-Based Tuning (Resonance)

Resonance tuning



- Resonance tuning(φ_r)
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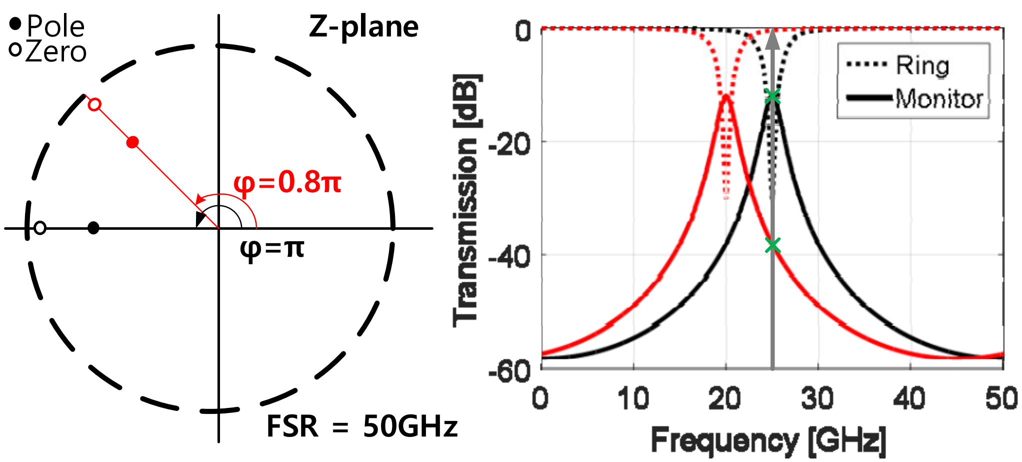
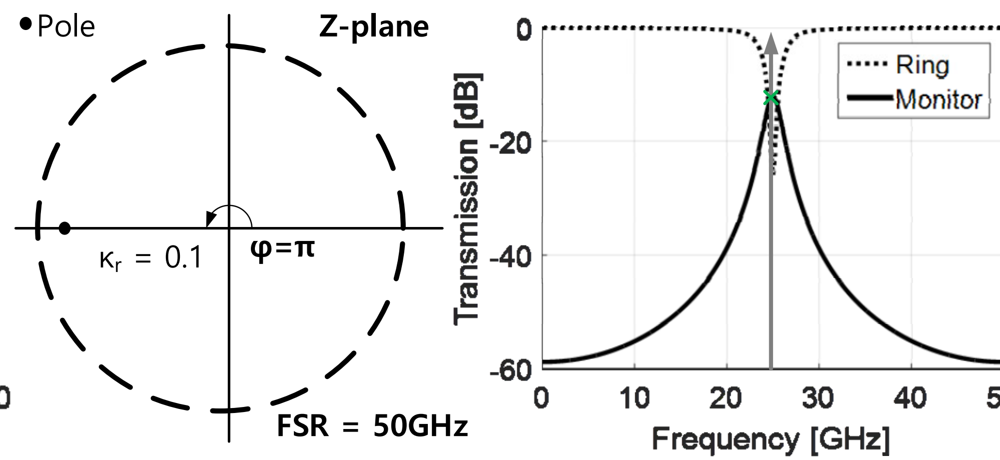
Monitor-Based Tuning (Coupling)

Resonance tuning



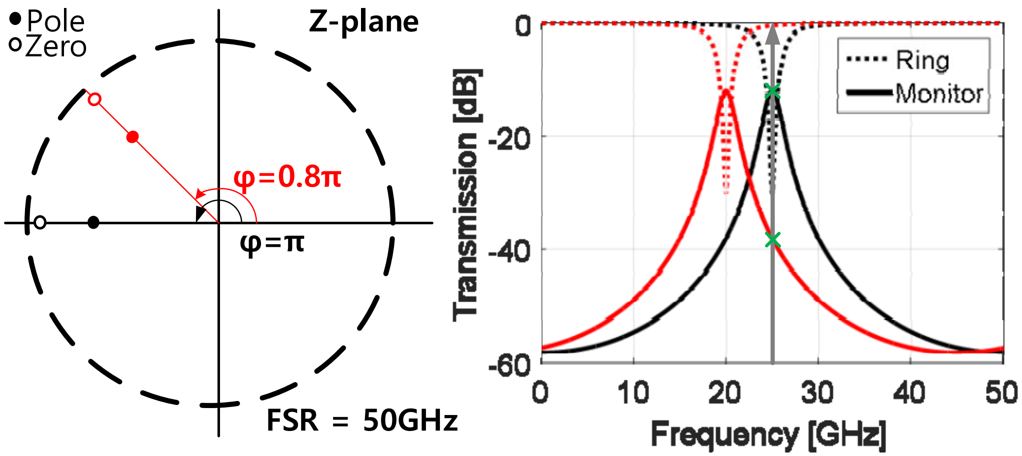
Coupling tuning



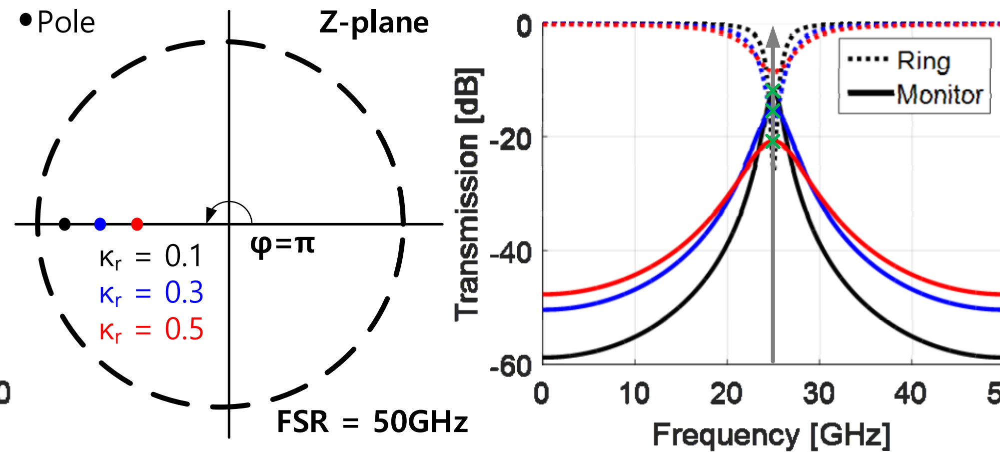
- Resonance tuning(φ_r)
  - Ring phase shifter shifts ORR's resonance frequency
  - Resonance is tuned to frequency stimulus by maximizing monitor reading
- Coupling tuning(κ_r)
  - Ring coupler setting changes peak value of the monitor response
  - Monitor response has the maximum reading at critical coupling

Monitor-Based Tuning (Coupling)

Resonance tuning



Coupling tuning



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  - Ring phase shifter shifts ORR's resonance frequency
  - Resonance is tuned to frequency stimulus by maximizing monitor reading
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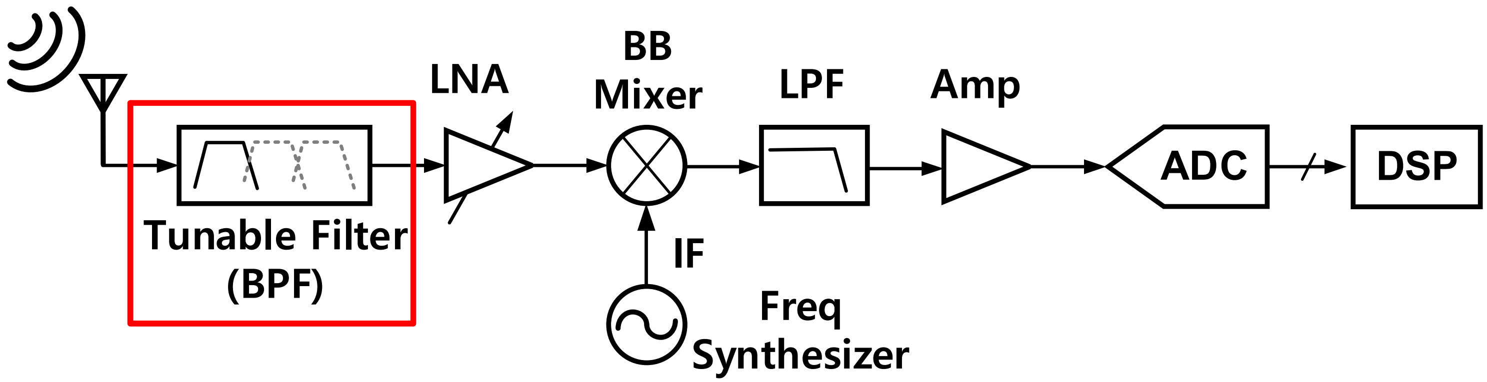
Broadband mm-wave Receiver

- System block diagram of mm-wave receiver



- Front-end filtering plays the critical role [3]
  - Guaranteeing the RF performance
  - Relaxing subsequent ADC and DSP requirements

- Multi-GHz tuning range, Bandwidth tunability, high out of band rejection are required to fit into the future filter requirements

[3] J. Capmany, J. Lightw. Technol, 2006

Limitation of Electrical Filtering Solution

- Off-chip surface acoustic wave (SAW) filters
  - High frequency, multi-band, large tuning range is not feasible[4]

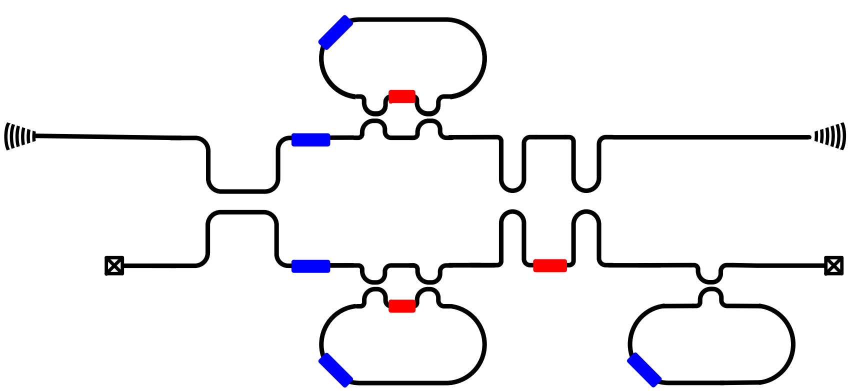
Off-chip SAW filters

- Integrated analog filters[5]
  - On-chip inductor Q-factor limits its selectivity, bandwidth
  - Active nature limit its linearity
- Integrated SAW-less receivers[6]
  - Proposed for dynamic bandpass filtering
  - Hard to extend operating frequency into mm-wave range

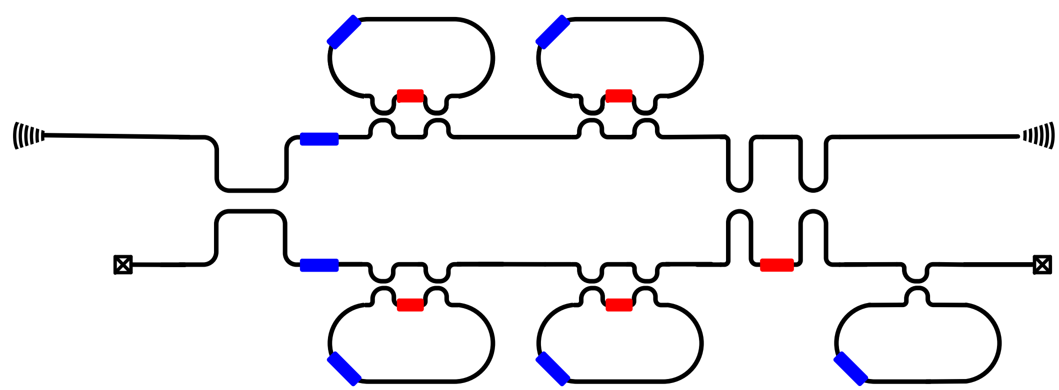
[4] A. Safarian, RFIC symposium, 2007
[5] F. Dulger, IEEE JSSC, 2003
[6] Y. Wu, IEEE TCAS II, 2003

All-pass Based Pole/Zero filter

- Basic pole/zero filter has half rings on top/bottom arms
- MZI couplers are implemented for bandwidth tunability and compensation of fabrication variations
- Additional Ring, end MZI coupler(k_{fe}), and front phase shifters ($\varphi_{fe,up}$, $\varphi_{fe,dn}$) are employed for rejection band tunability

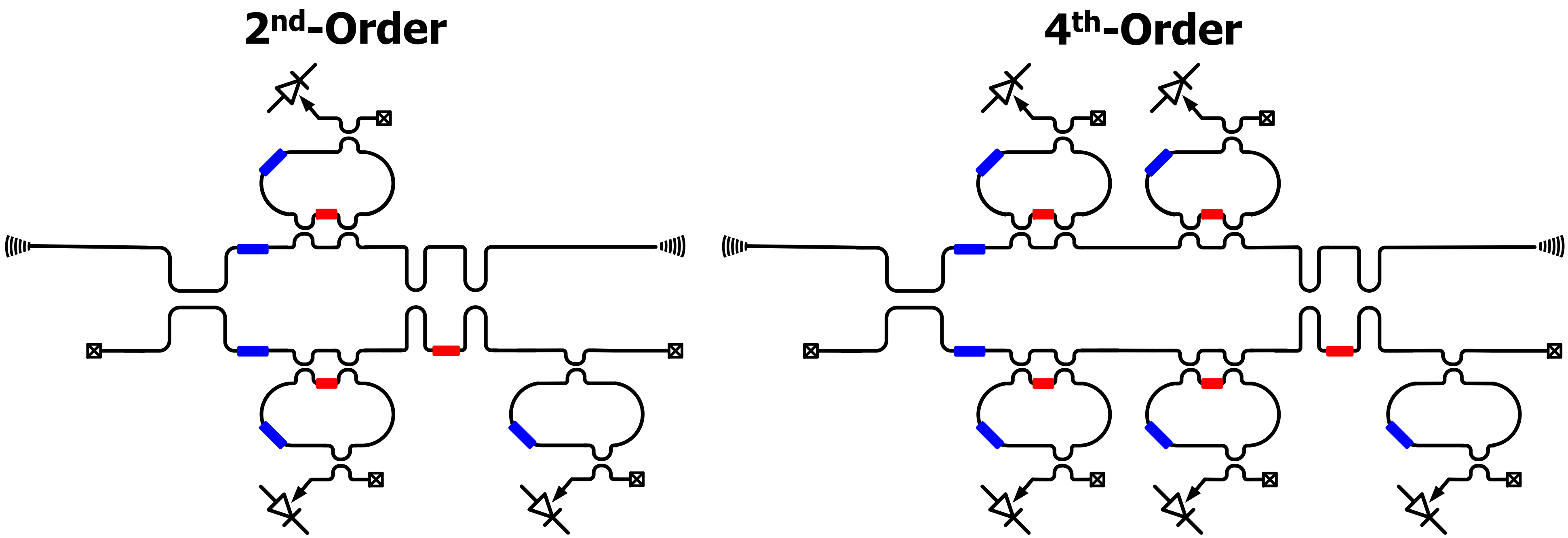


2nd-Order Filter



4th-Order Filter

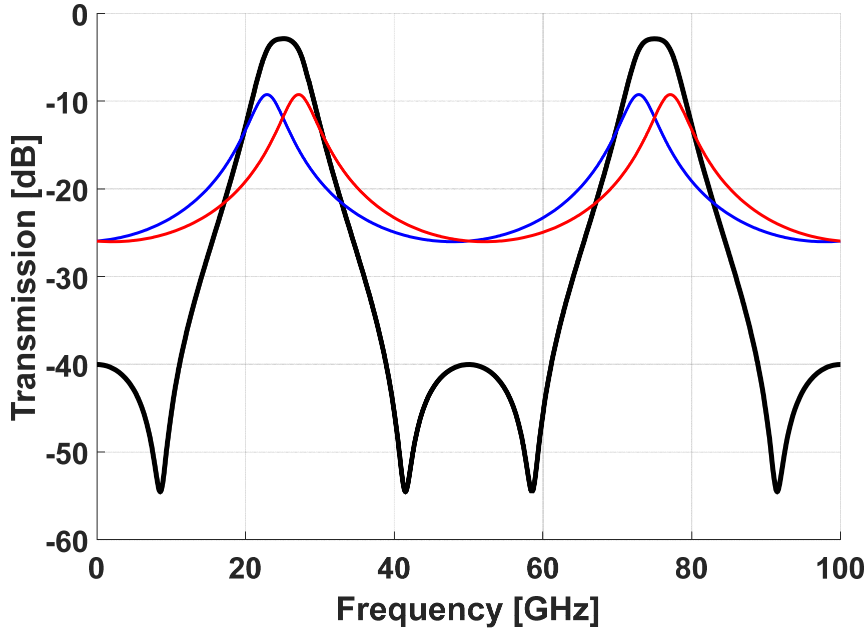
Modified All-Pass-Based Pole/Zero Filter



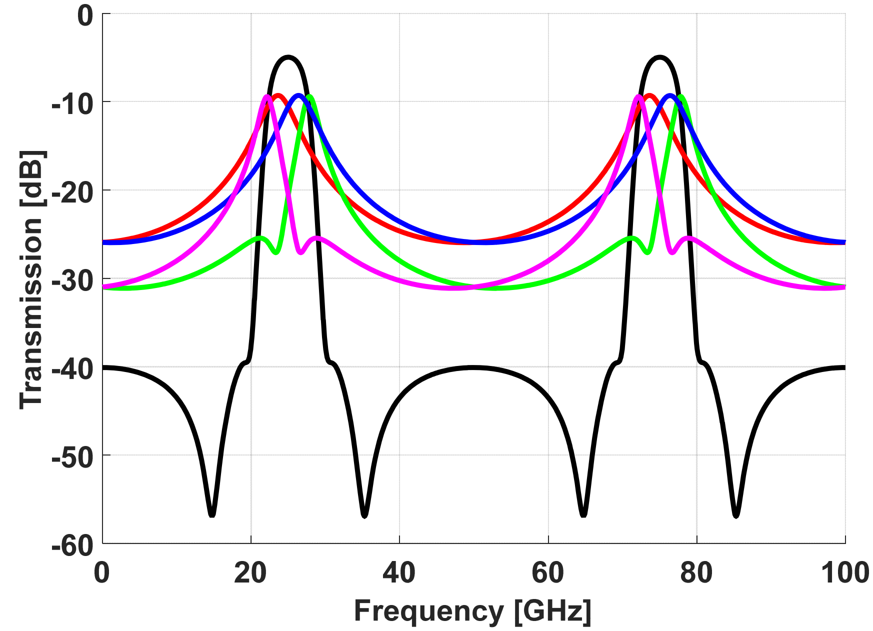
- Basic pole/zero filter has equal rings on top/bottom arms
- MZI couplers are implemented for bandwidth tunability and compensation of fabrication variations
- Additional ring, end MZI coupler(k_{fe}), and front phase shifters ($\varphi_{fe,up}$, $\varphi_{fe,dn}$) are employed for rejection band tunability
- Drop port with monitor PD are added to each ring to enable monitor-based automatic tuning

Simulated Filter Responses

2nd-Order



4th-Order

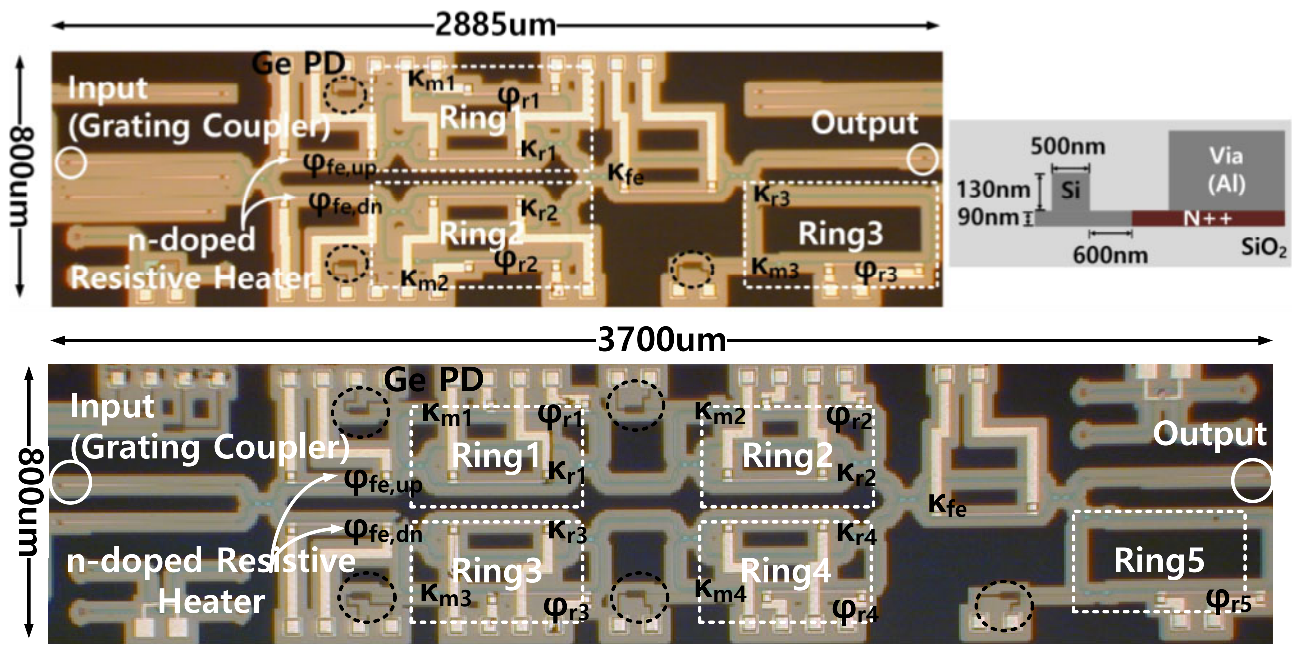


- Centered at 25GHz relative to 1550nm laser wavelength
- Optical waveguide propagation loss (RTL = 0.5dB) produces rounding in the passband
  - 2nd order 3dB bandwidth: 7GHz
  - 4th order 3dB bandwidth: 5GHz
- Monitor responses (k_m = 0.05) considered in simulation

Silicon Photonic Optical Filter Prototypes

2nd-Order

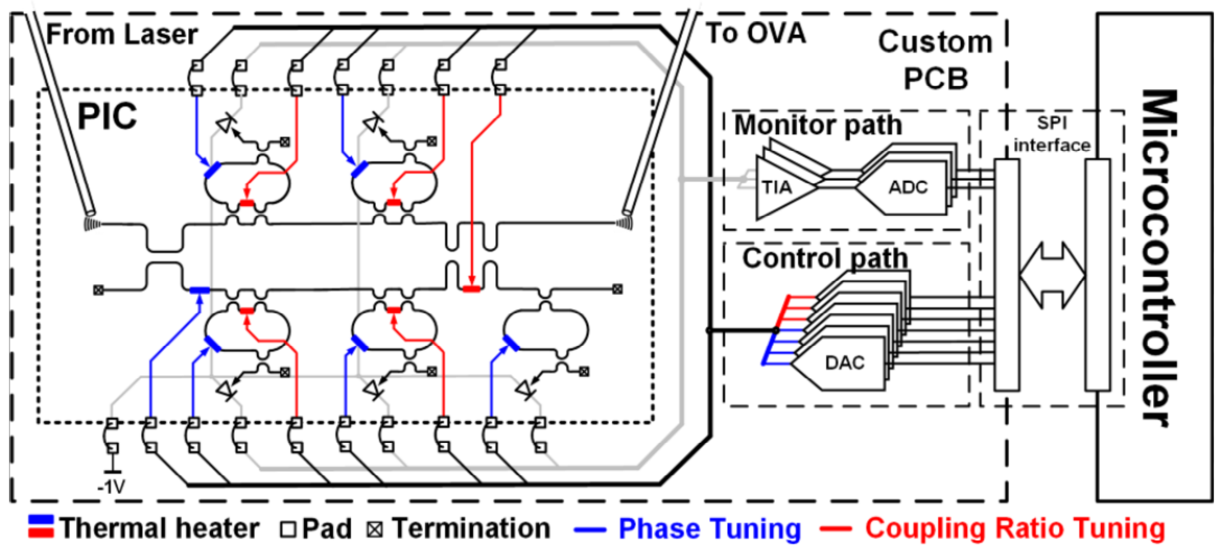
4th-Order



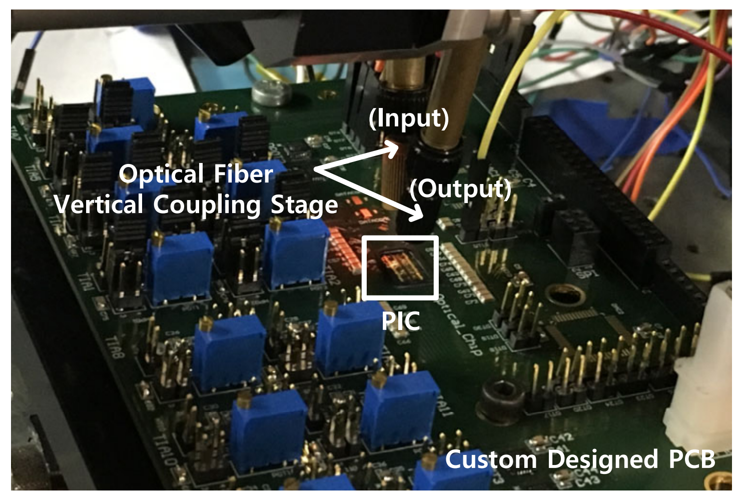
- Fabricated in IME SOI silicon photonics process
- Phase shifters are implemented with resistive heaters
- Rings are designed with 1554um circumference to provide a filter response with a 50GHz free spectral range

Filter Tuning System and Procedure

- Automatic tuning system
  - Microcontroller
  - DAC: heater control
  - TIA, ADC: monitor



- Tuning procedure
  1. Ring coupler tuning($\kappa_{r1,2}$)
  2. Resonance tuning ($\varphi_{r1,2,3}$)
  3. Rejection band tuning($\varphi_{fe,dn}$, κ_{fe})

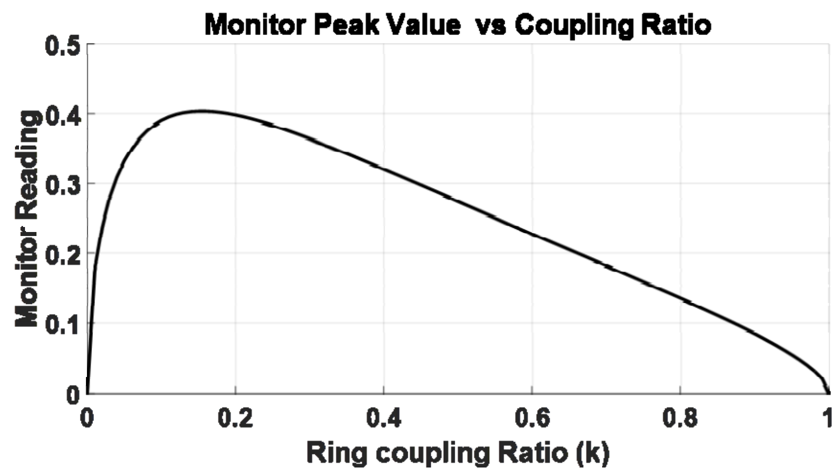


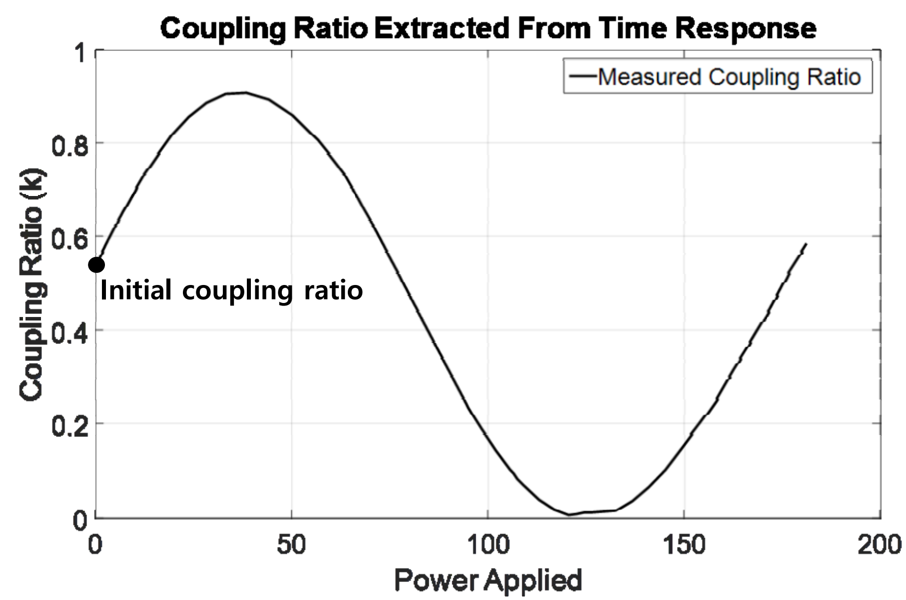
Tuning Procedure (1)

- Step 1: Ring coupler tuning($\kappa_{r1,2}$)

  (1) Find critical coupling ratio

  - Initial coupling ratio can deviate from the designed value (process variation)



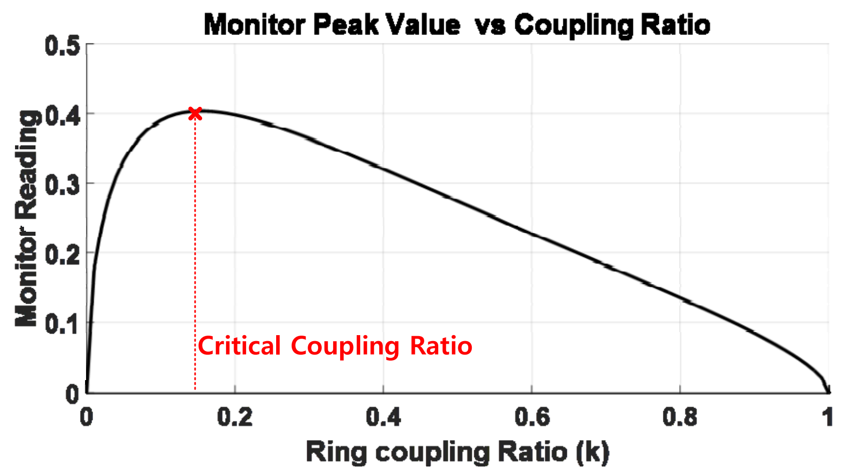


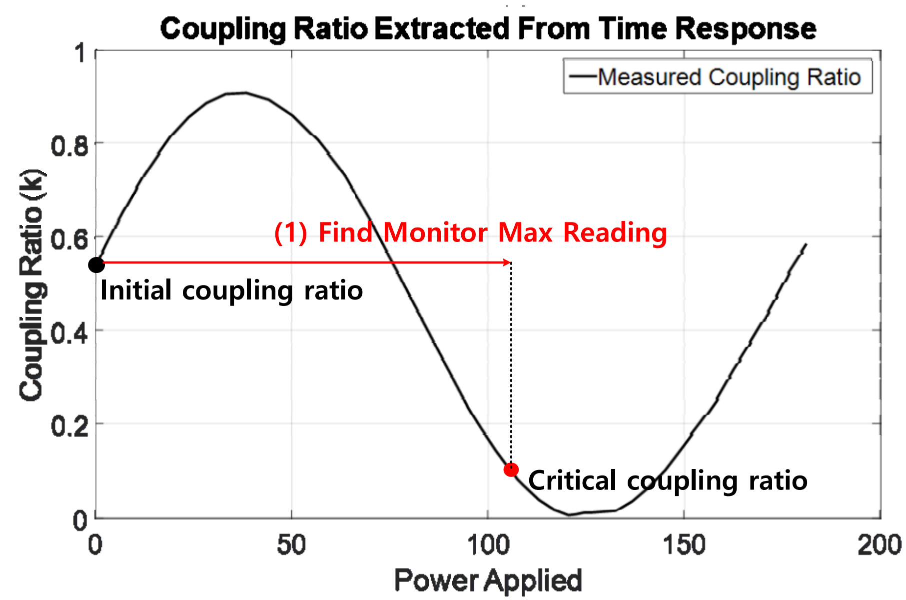
Tuning Procedure (1)

- Step 1: Ring coupler tuning($\kappa_{r1,2}$)

  (1) Find critical coupling ratio

  - Initial coupling ratio can deviate from the designed value (process variation)
  - Critical coupling shows maximum monitor reading and serves as a reference point





Tuning Procedure (1)

- Step 1: Ring coupler tuning($\kappa_{r1,2}$)

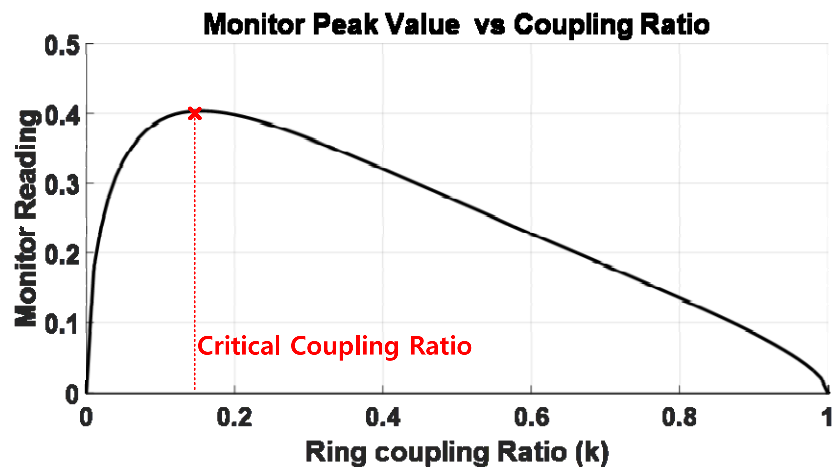
  (1) Find critical coupling ratio

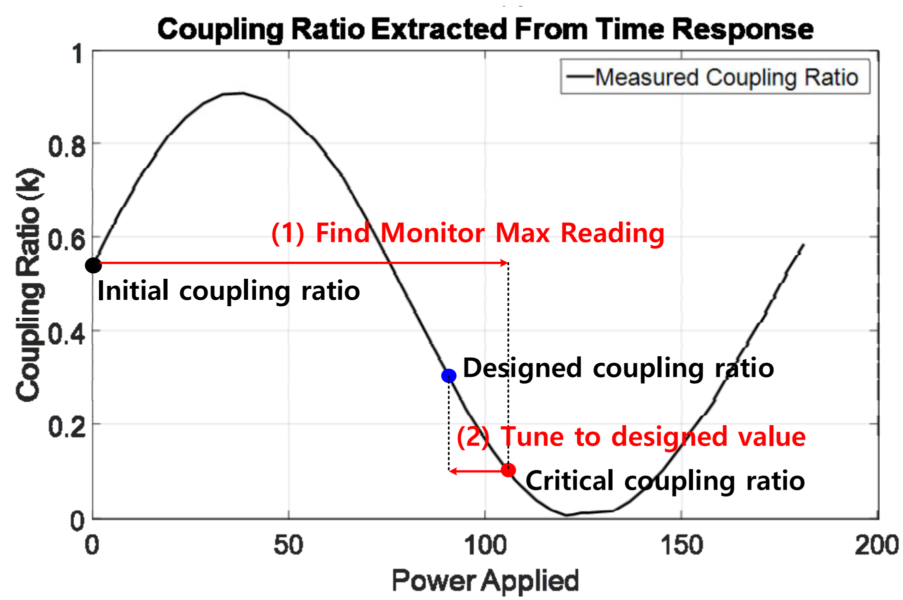
  - Initial coupling ratio can deviate from the designed value (process variation)
  - Critical coupling shows maximum monitor reading and serves as a reference point

  (2) Tune to designed coupling ratio

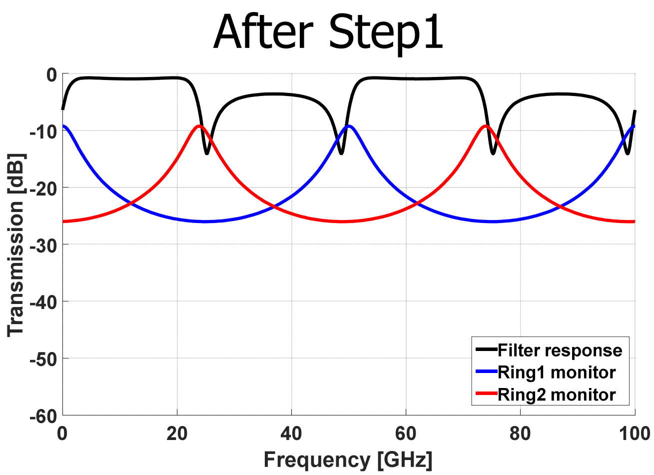
  - Coupling ratio follows MZI characteristic

Coupler tuning also shifts the ring's resonance which is corrected with the ring resonance tuning procedure

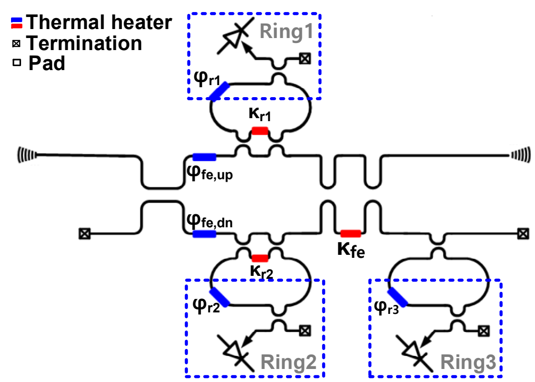




Tuning Procedure (2)



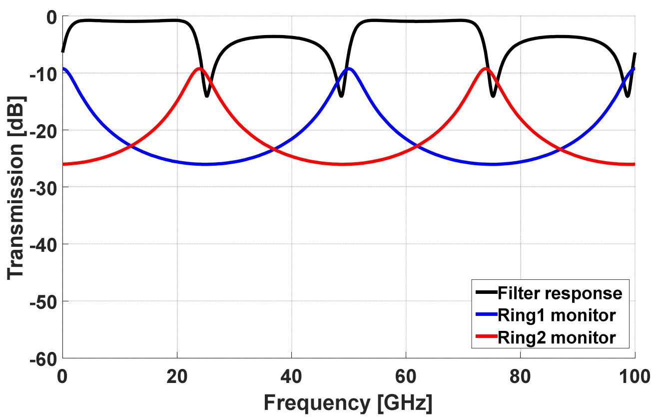
- Step 2: Resonance Tuning($\varphi_{r1,2,3}$)



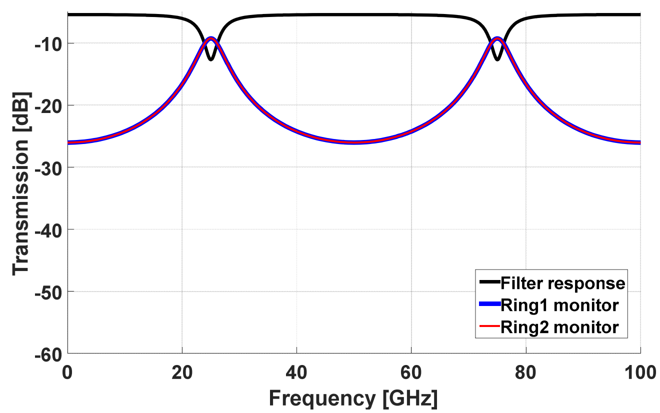
2nd-Order APF-based Pole/Zero Filter

Tuning Procedure (2)

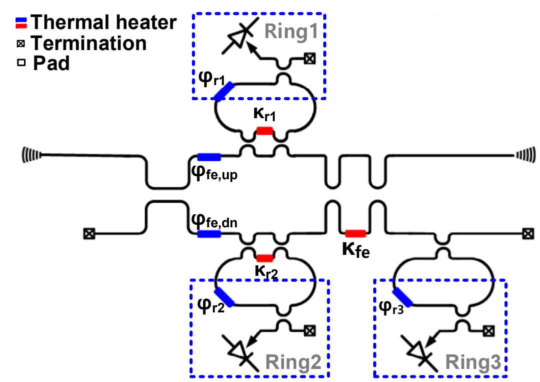
After Step1



Ring1,2 tuned to center frequency



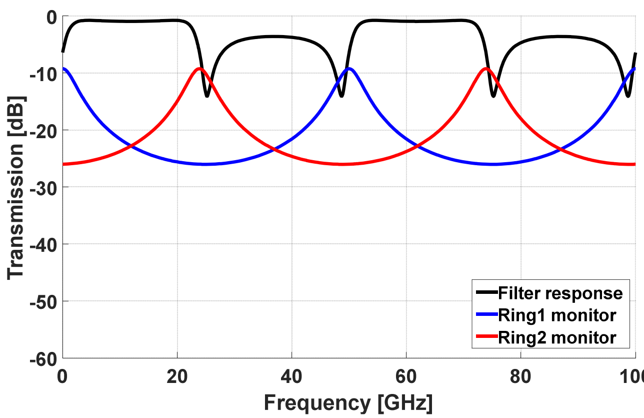
- Step 2: Resonance Tuning($\varphi_{r1,2,3}$)
  - Tune Ring1,2 to the center frequency
  - Ring3 is also tuned to the null frequency for rejection band tuning and reduced sensitivity to thermal cross talk
  - Multiple iterations are performed due to thermal crosstalk



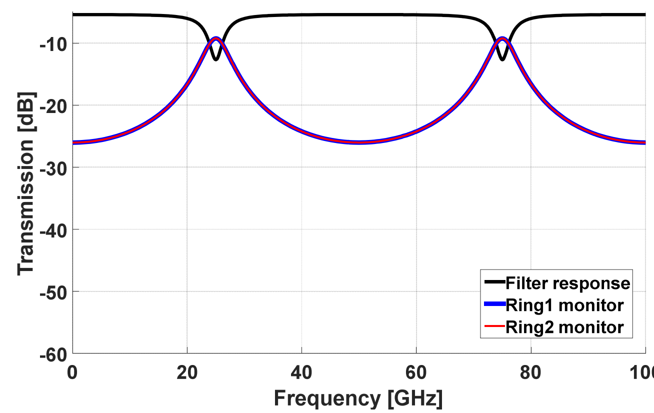
2nd-Order APF-based Pole/Zero Filter

Tuning Procedure (2)

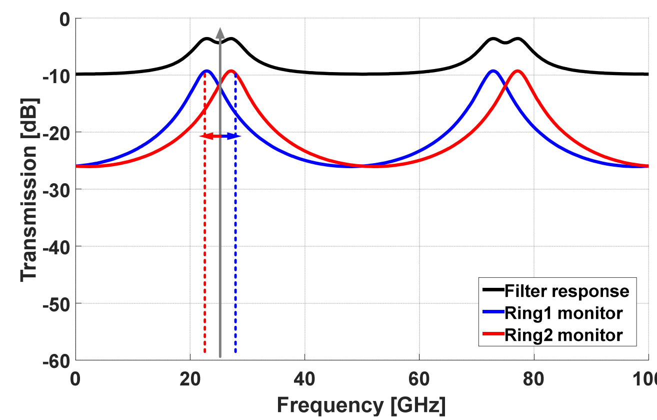
After Step1



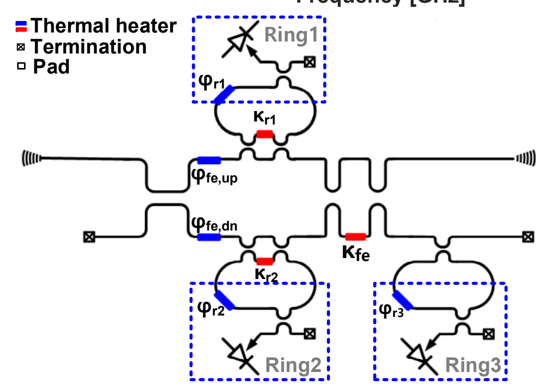
Ring1,2 tuned to center frequency



After Step2

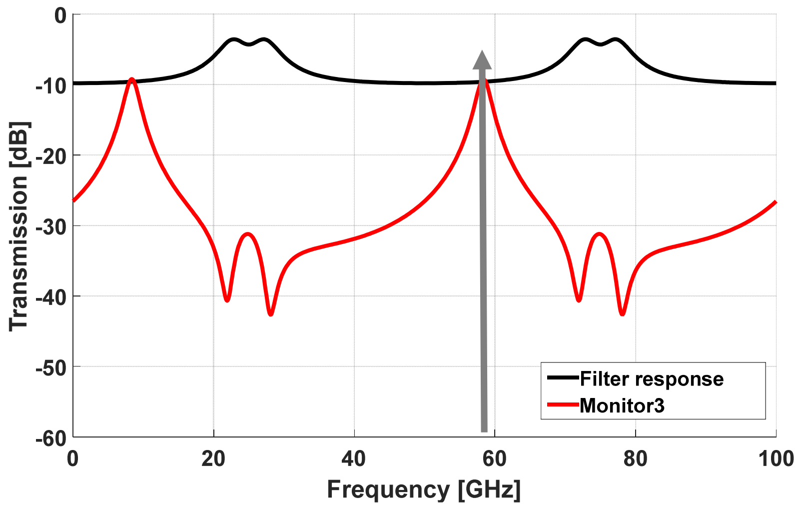


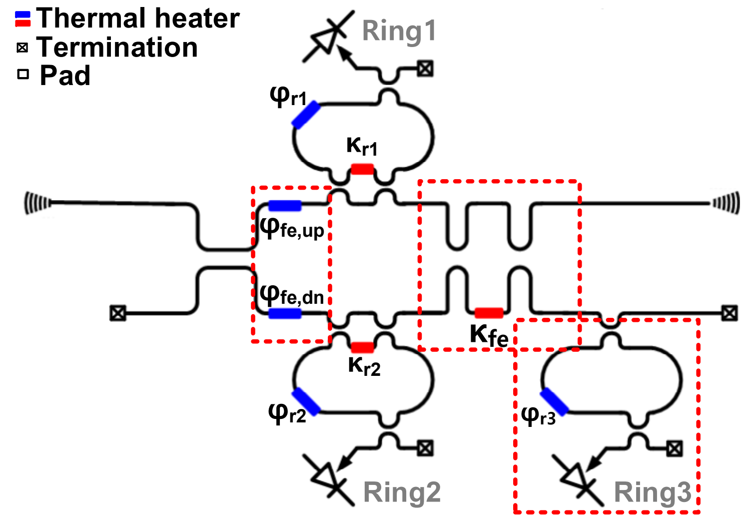
- Step 2: Resonance Tuning($\varphi_{r1,2,3}$)
  - Tune Ring1,2 to the center frequency
  - Ring3 is also tuned to the null frequency for rejection band tuning and reduced sensitivity to thermal cross talk
  - Multiple iterations are performed due to thermal crosstalk
  - Ring1,2 are blue/red shifted to yield appropriate monitor reading and set the filter bandwidth



2nd-Order APF-based Pole/Zero Filter

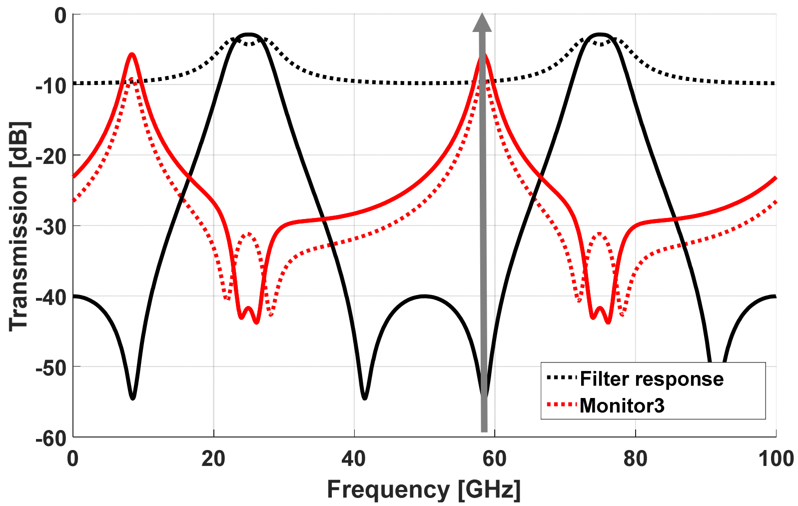
Tuning Procedure (3)

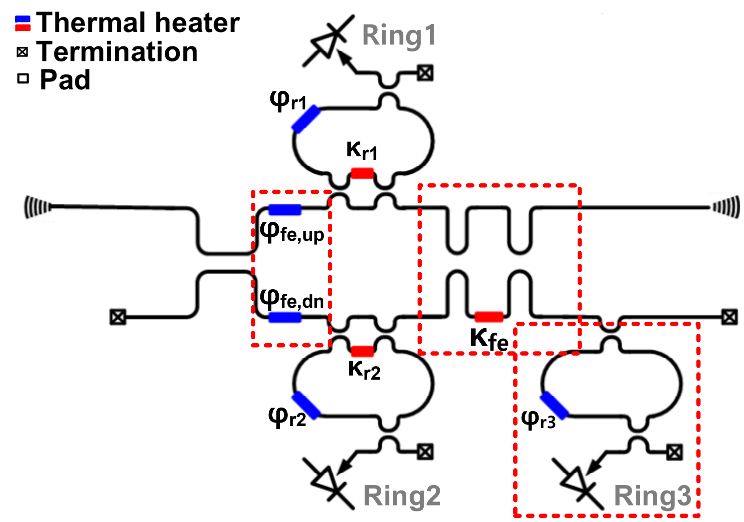




- Step 3: Rejection Band Tuning($\varphi_{fe,dn}$, κ_{fe})
  - Ring3 is placed at the complementary port of the filter response
  - Input laser frequency is switched to null frequency of filter response

Tuning Procedure (3)

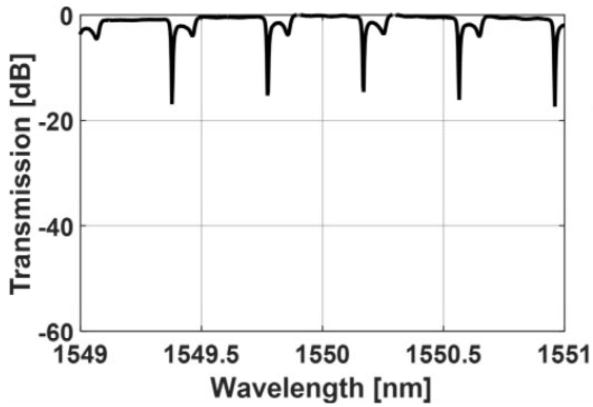




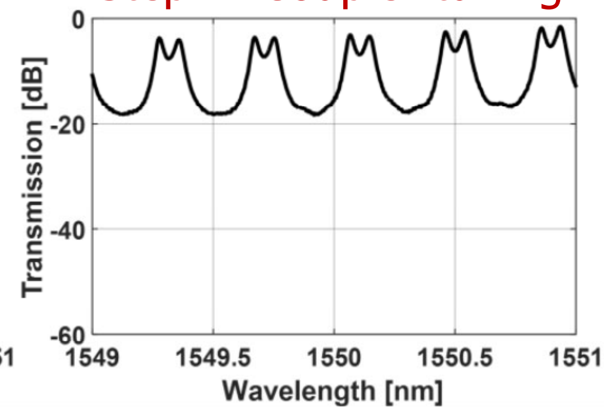
- Step 3: Rejection Band Tuning($\varphi_{fe,dn}$, κ_{fe})
  - Ring3 is placed at the complementary port of the filter response
  - Input laser frequency is switched to null frequency of filter response
  - Maximizing the monitor3 reading at the null frequency lowers the out of band rejection of the filter response
  - While tuning rejection band, resonance tuning of ring3 is also performed to monitor the maximum value

Measured 2nd-order Filter Initial Calibration

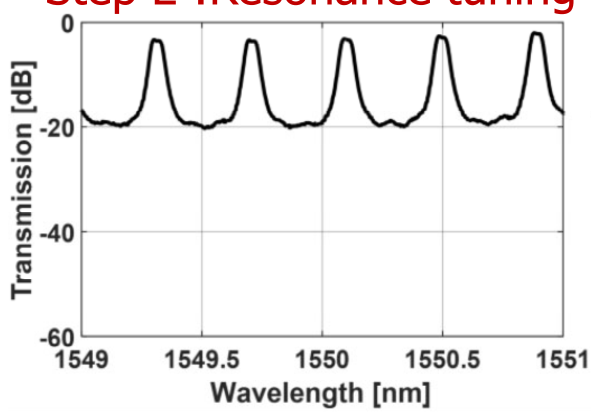
Initial



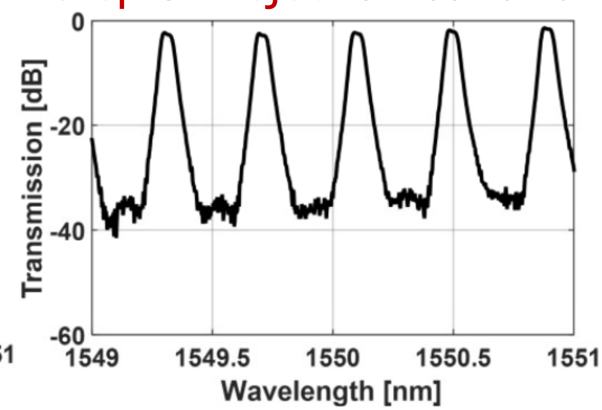
Step 1: Coupler tuning



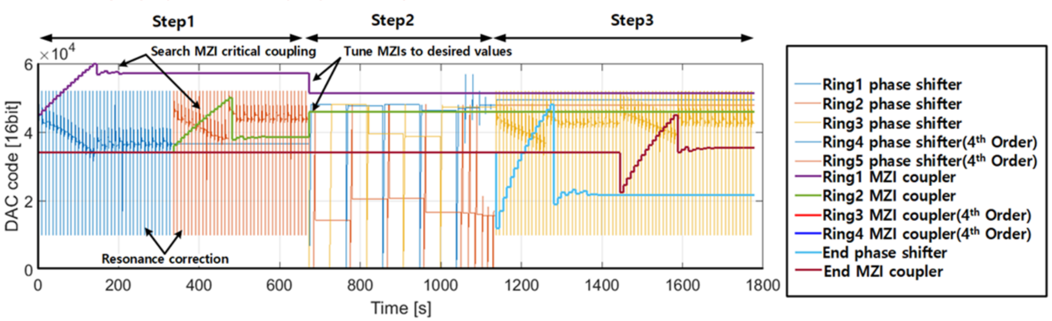
Step 2 :Resonance tuning



Step 3: Rejection band tuning

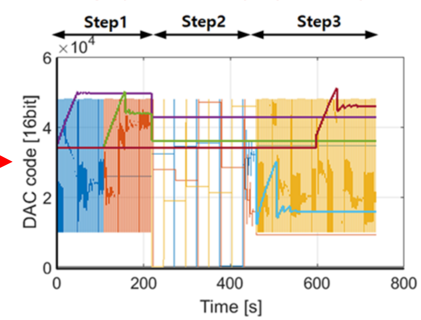


750um Substrate

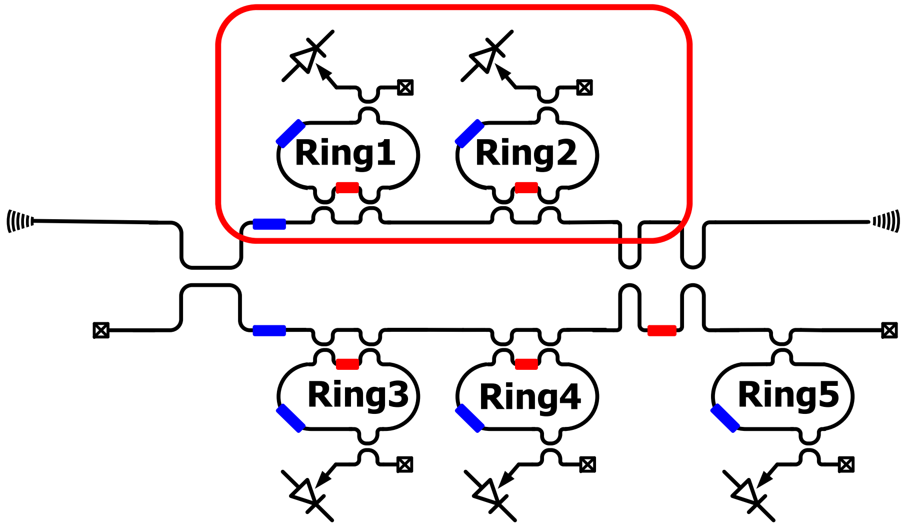


1042s reduction

75um Substrate



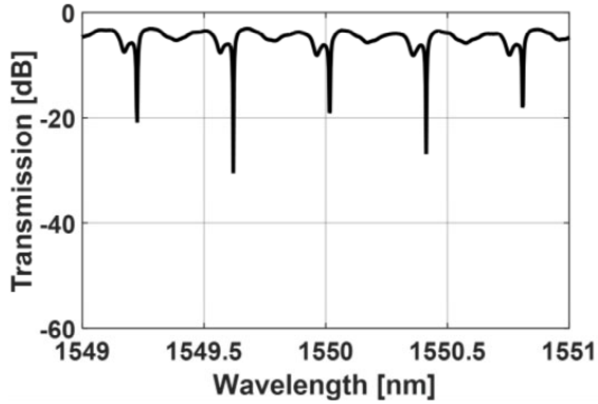
4th-order Filter Tuning



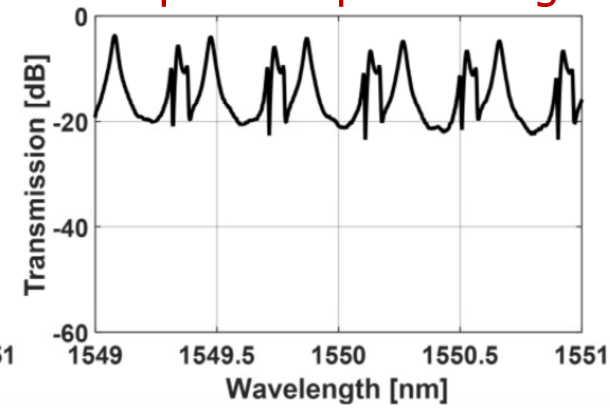
- What is different from the 2nd-order filter tuning?
  - Since two rings are cascaded, Ring2 and Ring4 monitor responses are influenced by the Ring1 and Ring3 response
  - Ring1/3 coupling factors are set to zero in order to tune Ring2/4 coupling
  - Increased number of iterations due to thermal crosstalk

Measured 4th-order Filter Initial Calibration

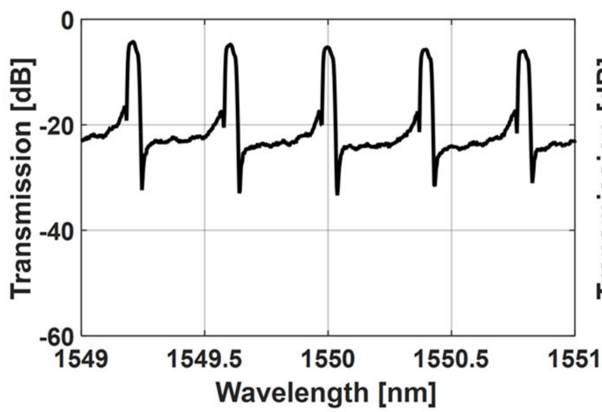
Initial



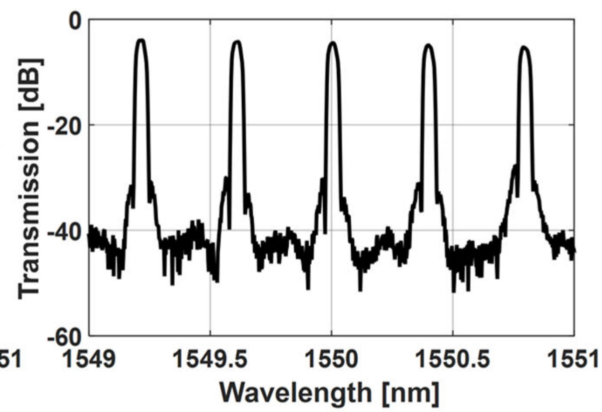
Step 1: Coupler tuning



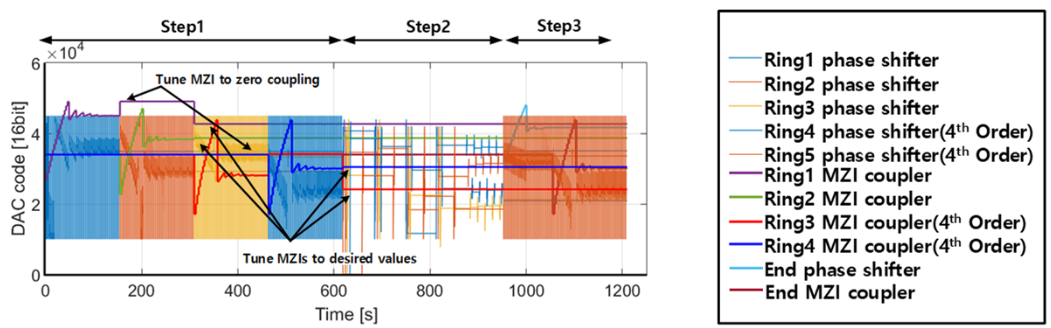
Step 2 :Resonance tuning



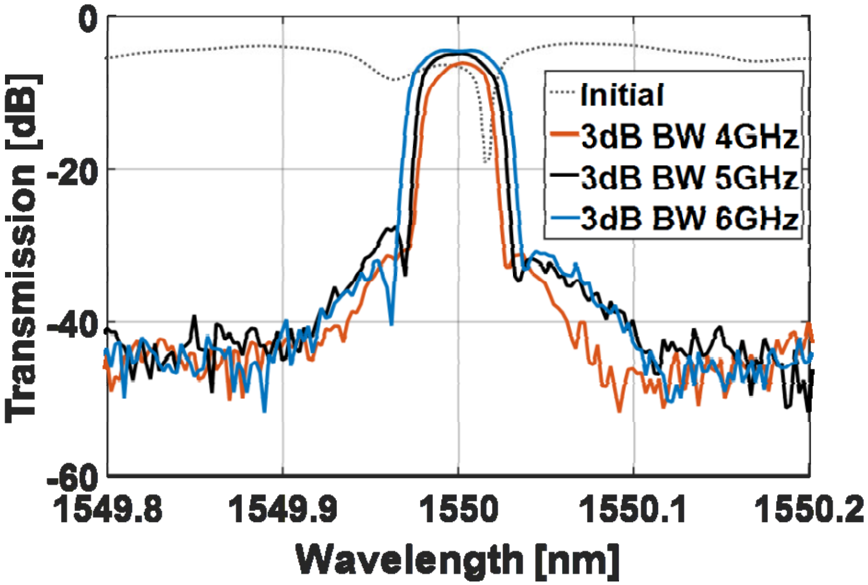
Step 3: Rejection band tuning

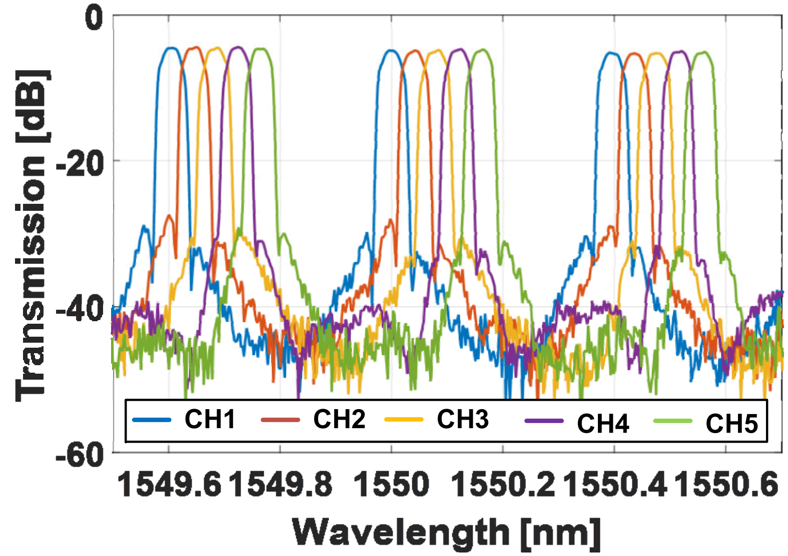


w/ 75um Substrate



4th-order Filter Reconfiguration





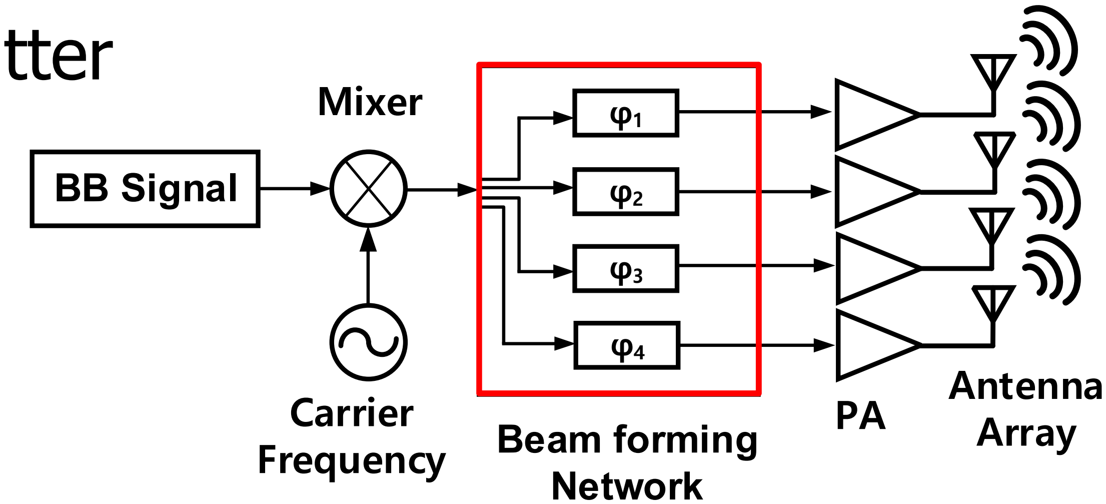
- Bandwidth reconfiguration to 4GHz and 6GHz 3dB BW
- Center frequency reconfiguration with 0.04nm spacing
  - 5 different calibrations performed with different laser center frequencies
  - After full calibration, center frequency switching only takes 300ms

Outline

- Motivation
- Monitor-Based Tuning Principles
- Automatic Filter Tuning
- Automatic Optical Beamforming Network Tuning
- Conclusion

True Time Delay Beamforming Network

- Phased array transmitter



- Beamforming network plays a critical role [3]
  - -Beam focusing to the specific direction
  - -Beam steering functionality

- Multi-GHz bandwidth, mm-wave frequency operation and high resolution beam angle tuning are required to fit into the 5G communication

[3] J. Capmany, J. Lightw. Technol, 2006

Limitation of Electrical Beamforming Solution

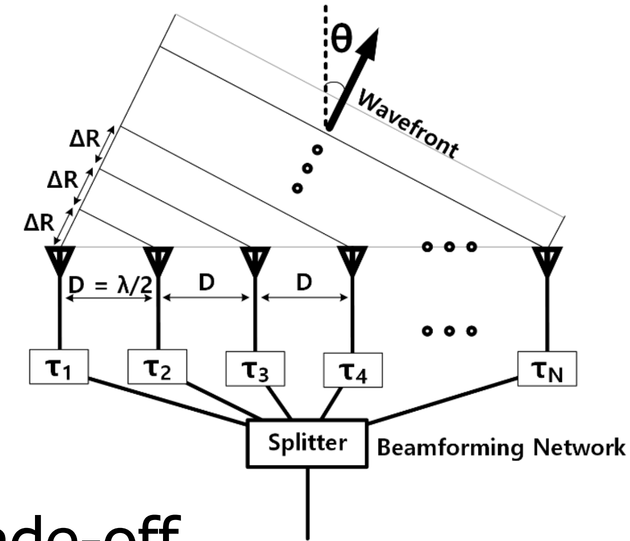
- Most of electrical beamforming network employ phase shifters in their RF path
  - Inherently narrow band
  - Beam radiation angle is dependent on the RF frequency (Beam squint)
  - Limited phase resolution (Discrete tuning)
  - Passive phase shifters are lossy
  - Active phase shifters are power hungry, linearity limited.

- Timed delay beamforming network
  - Squint free
  - Limited resolution (Discrete tuning)
  - Bulky and integration into CMOS is challenging

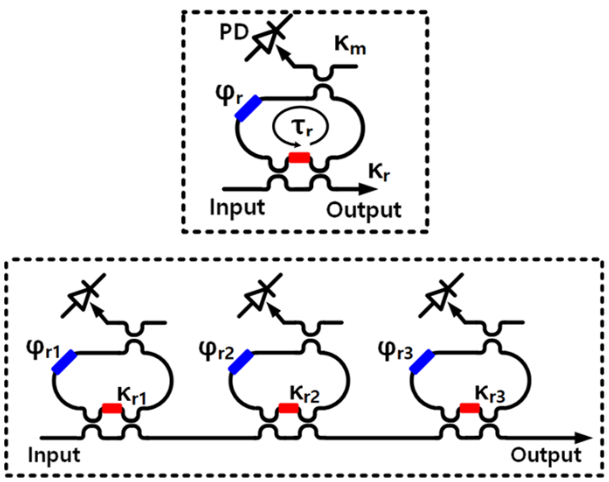
Beamforming Network Principle

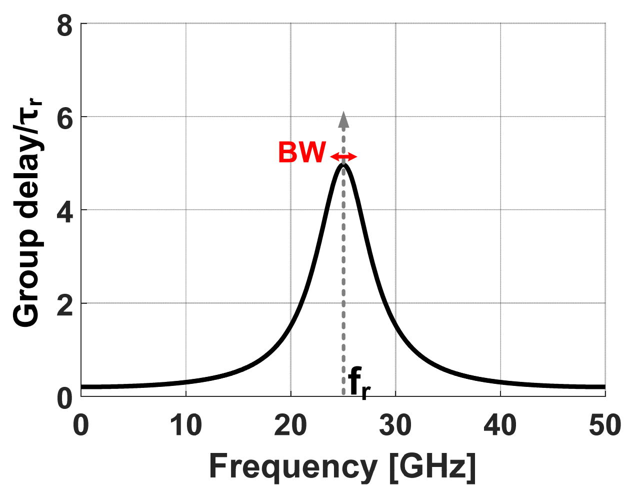
- Beamforming Network
  Delay(τ) in Beamforming network
  for radiating angle(θ) at the linear array

$$D = \frac{\lambda}{2} \qquad \Delta R = D \cdot sin\theta \qquad \Delta\tau = D \cdot cos\theta / c$$

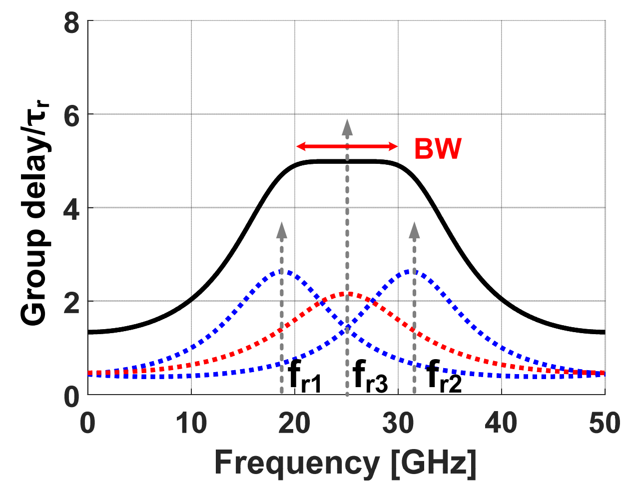


- Single ORR has bandwidth-group delay trade-off
- Cascaded ORR can break the trade-off





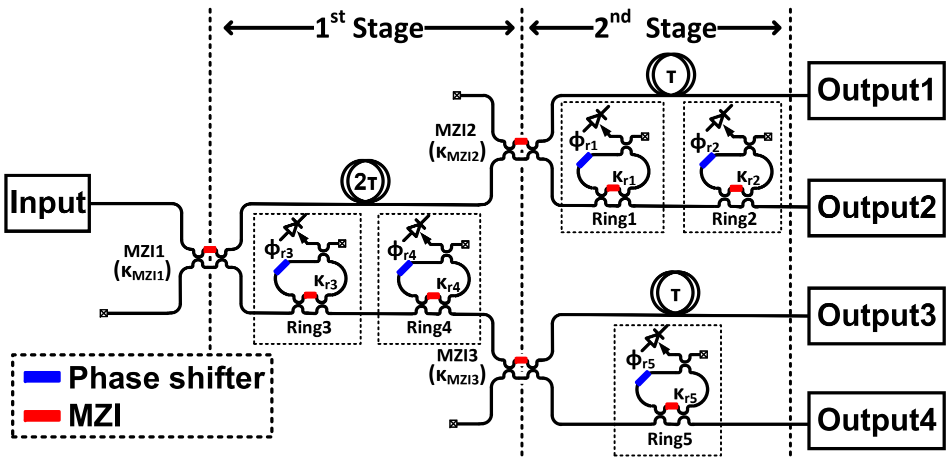
Single ORR



Cascaded ORR

Optical Beamforming Network (OBFN) Design

- Asymmetric binary tree structure
- Operating frequency: 30GHz
- Target Bandwidth: 2GHz
- Free spectral range: 50GHz
- Beam steering angle
  -30° ~ 30° (150° ~ 210°)

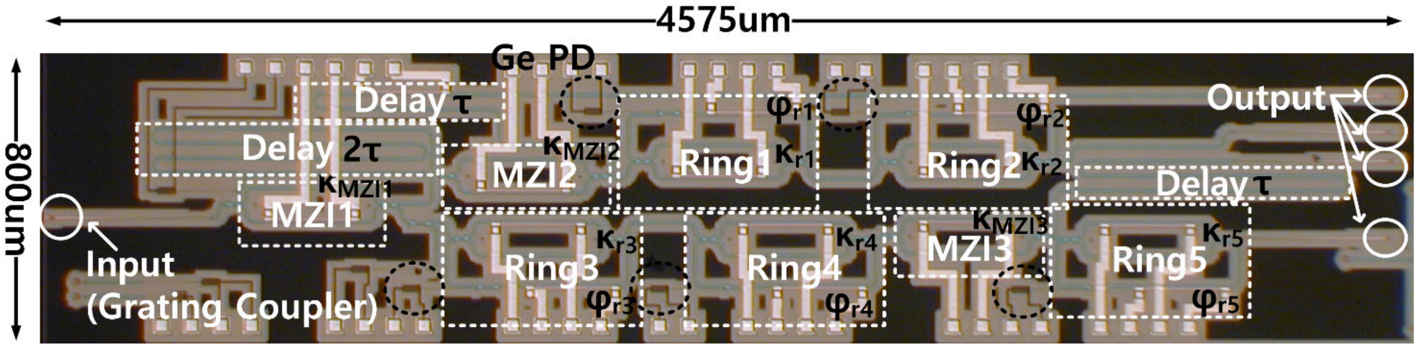


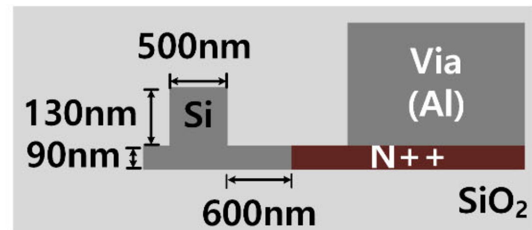
Group Delay Requirements

Radiating Angle (θ)	Output1	Output2	Output3	Output4
$\theta = 150$ °	0.0ps	25.0ps	50.0ps	75.0ps
	(0ps + 0ps)*	(-24.4ps + 50.5ps)	(-51ps + 101ps)	(-76.ps + 151.5ps)
$\theta = 165$ °	0.0ps	29.0ps	58.0ps	87ps
	(0ps + 0ps)	(-25.5ps + 54.5ps)	(-51.0ps + 109.0ps)	(-76.5ps + 163.5ps)
$\theta = 180°$	0.0ps	33.3ps	66.7ps	100.0ps
	(0ps + 0ps)	(-25.5ps + 58.8ps)	(-51.0ps + 117.7ps)	(-76.5ps + 176.5ps)
$\theta = 195°$	0.0ps	37.6ps	75.3ps	112.9ps
	(0ps + 0ps)	(-25.5ps + 63.1ps)	(-51.0ps + 126.3ps)	(-76.5ps + 189.4ps)
$\theta = 210°$	0.0ps	41.6ps	83.3ps	124.9ps
	(0ps + 0ps)	(-25.5ps + 67.2ps)	(-51.0ps + 134.3ps)	(-76.5ps + 201.4ps)

*Group delay (red: path delay, blue: ORR delay)

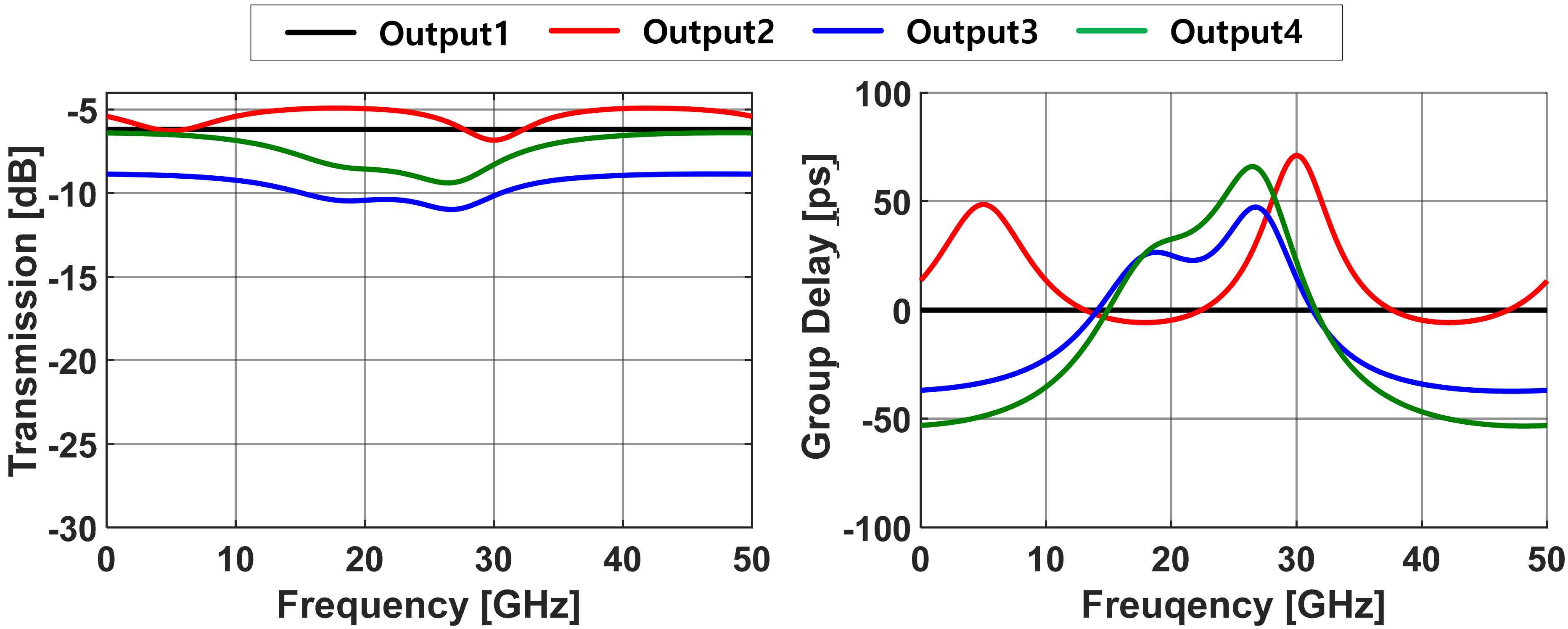
Silicon Photonic OBFN Prototype





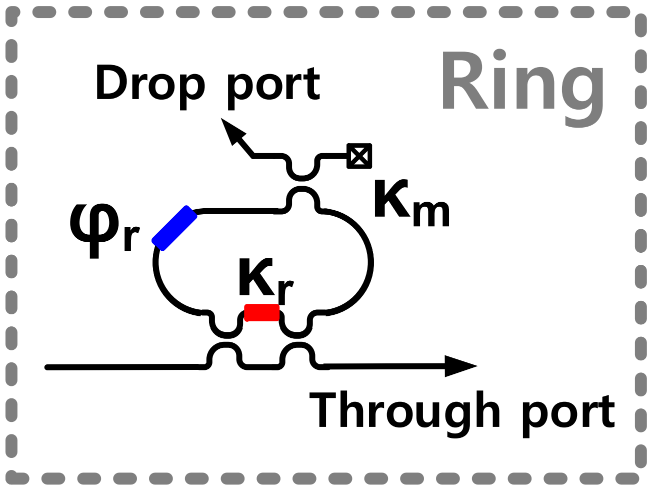
- Fabricated in IME SOI silicon photonics process
- Phase shifters are implemented with resistive heaters
- Rings are designed with 1554um circumference to provide an OBFN response with 50GHz free spectral range
- Delay lines (τ) are designed with 1554um length

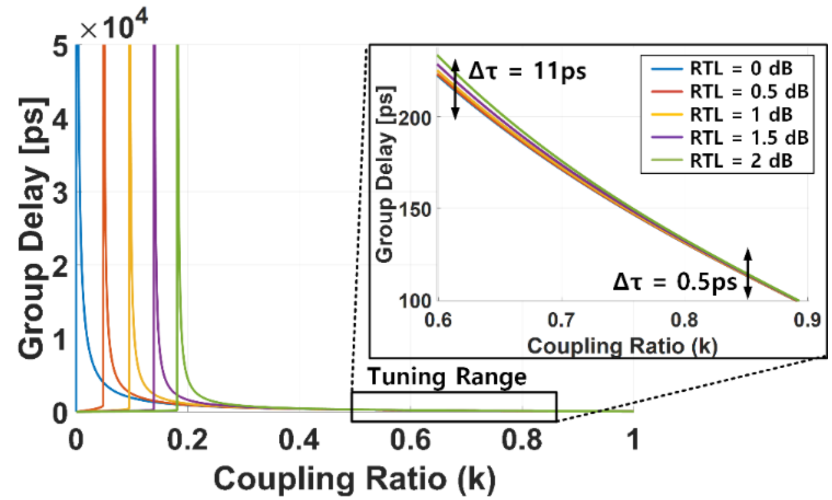
Si-Photonic OBFN w/ Process Variations



- Photonic devices are vulnerable to process and temperature variations
- Significant variation in 4-channel output power and group delay
- Need precise automatic calibration solution

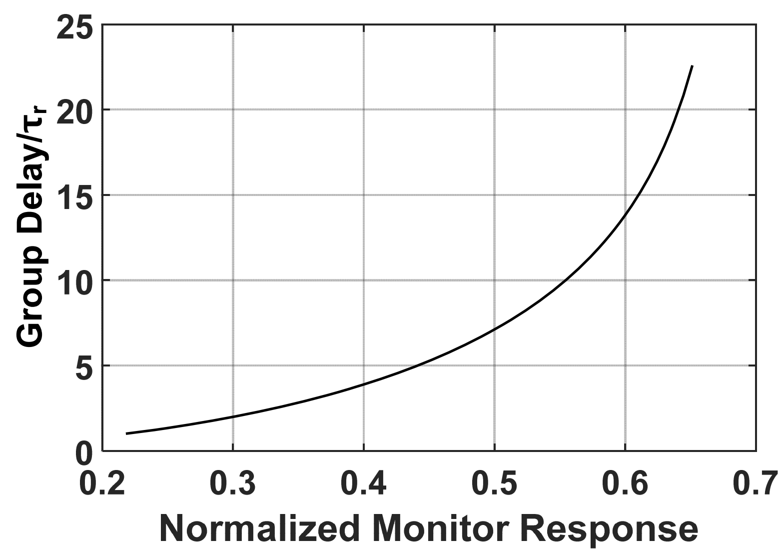
ORR Group Delay Response



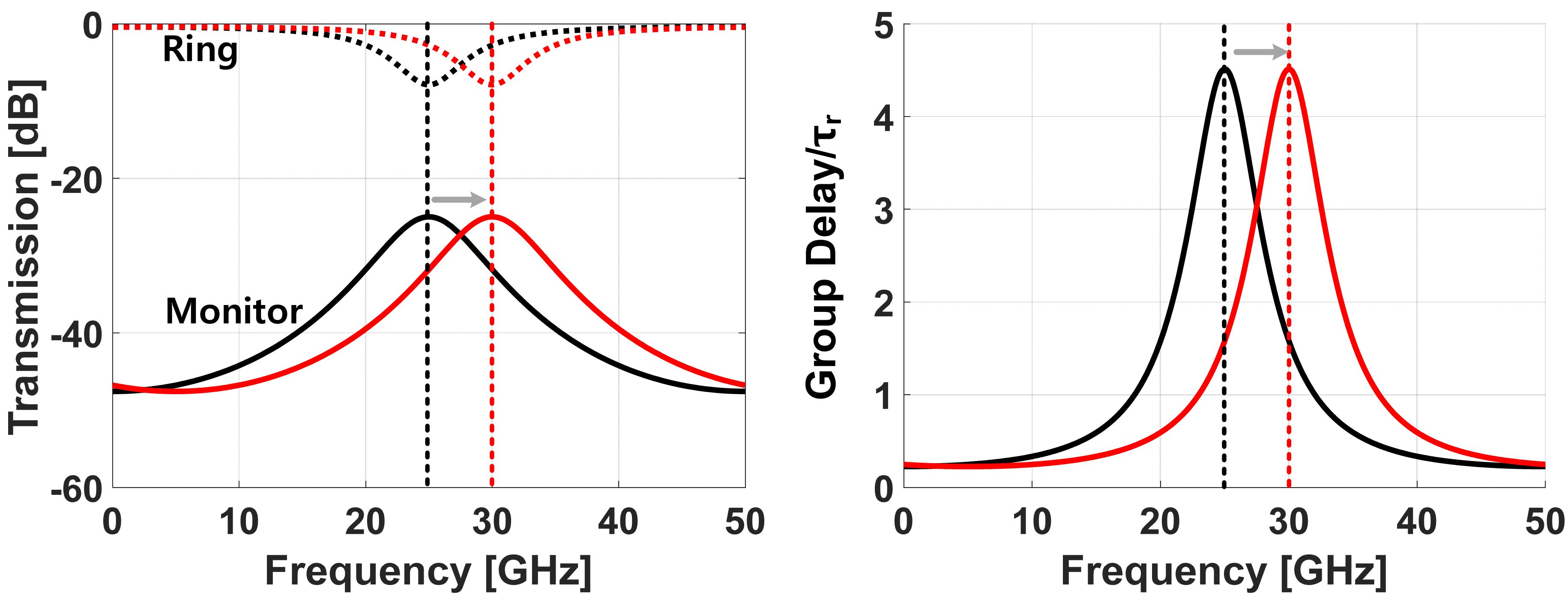


$$\tau_g(f) = \frac{\kappa_r \tau_r}{r(2-\kappa_r) - (1+r^2)\sqrt{1-\kappa_r}\cos(2\pi f \tau_r + \phi_r)}$$

- ORR's coupling ratio and round trip loss (RTL) determines group delay peak value
- Group delay can be tuned based on monitor response

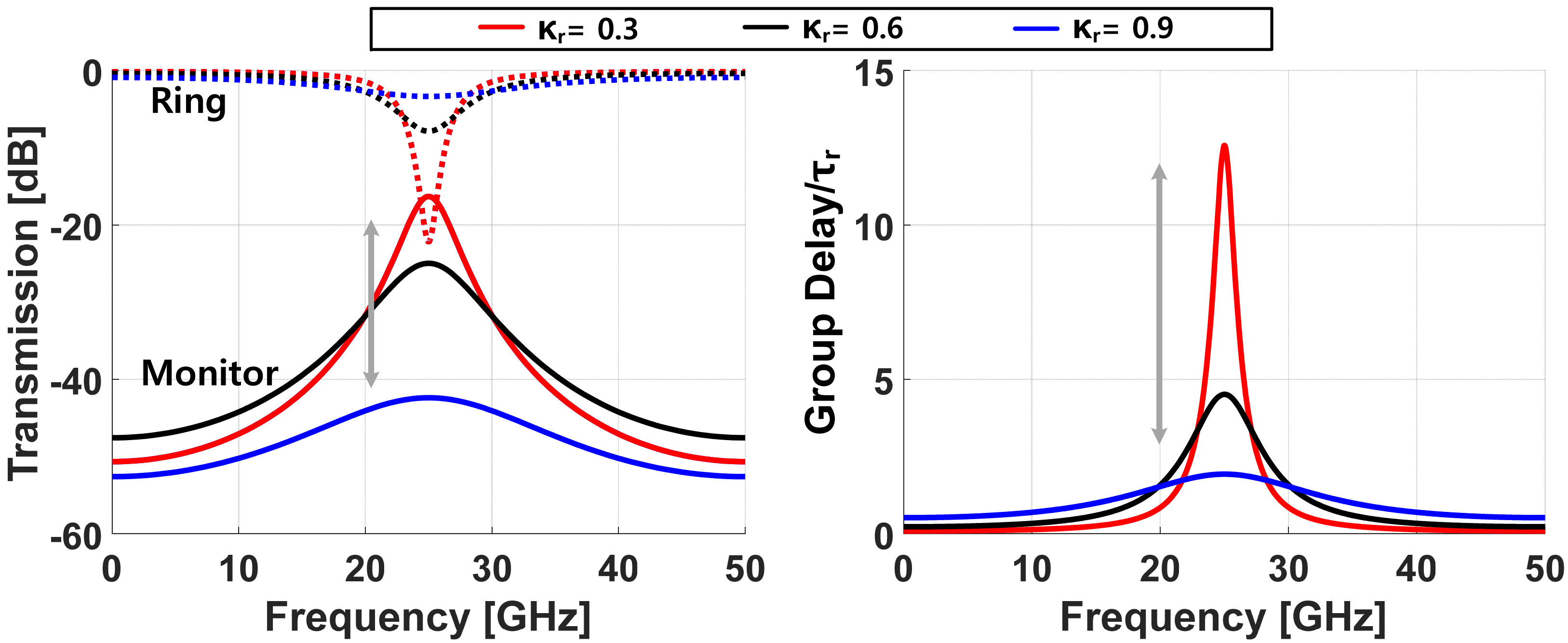


Monitor-Based Group Delay Tuning

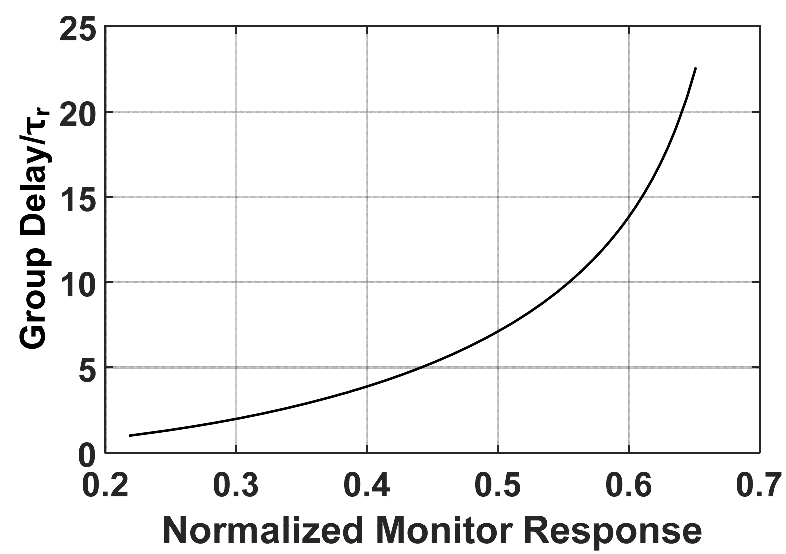


- Through-port group delay resonance is also aligned with through-port and drop-port magnitude resonance
- ORR group delay resonance can be tuned to the desired frequency through the ring resonance tuning procedure

Monitor-Based Group Delay Tuning

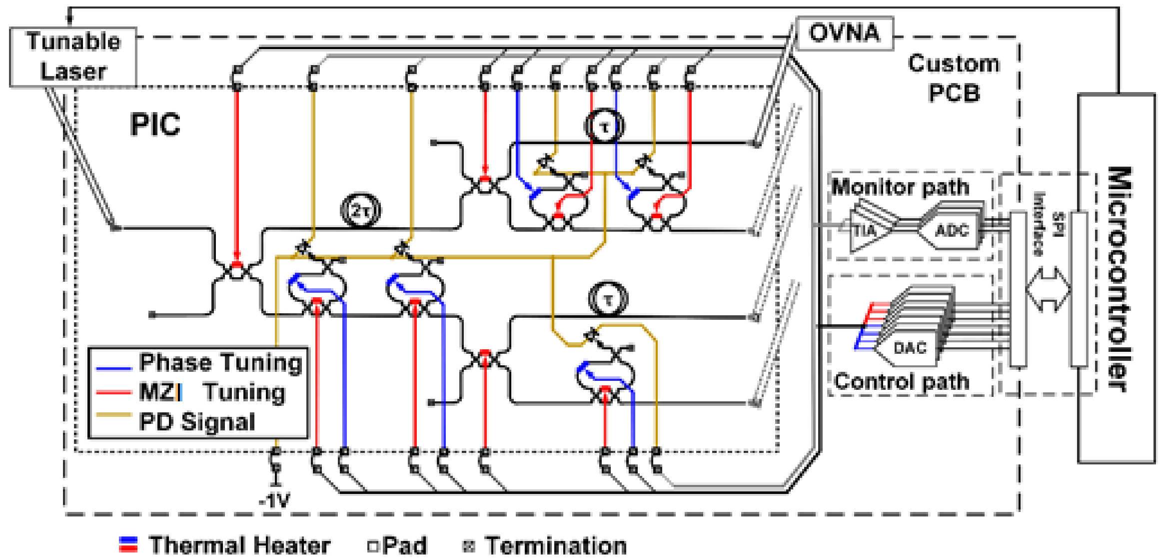


- Tuning of the coupling ratio can achieve the desired group delay response

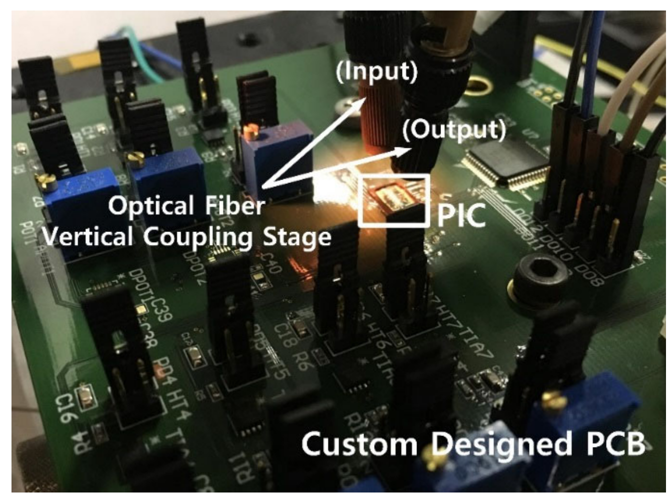


OBFN Tuning System and Procedure

- Automatic tuning system
  - Microcontroller
  - DAC: heater control
  - TIA, ADC: monitor

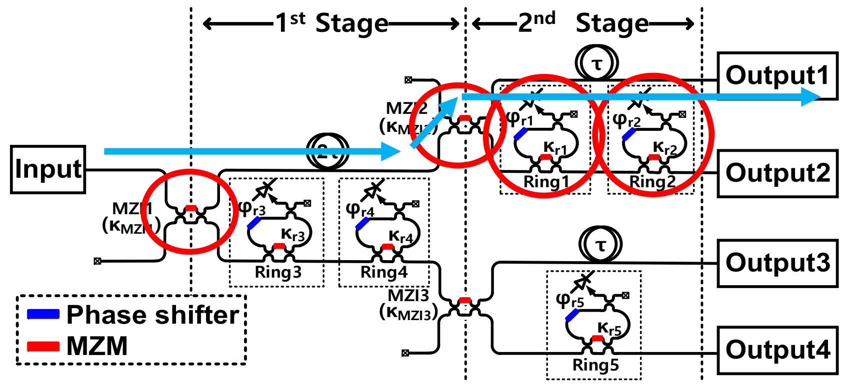


- Tuning procedure
  1. Output1 & 2 path tuning
  2. Output3 path tuning
  3. Output4 path tuning
  4. Resonance tuning

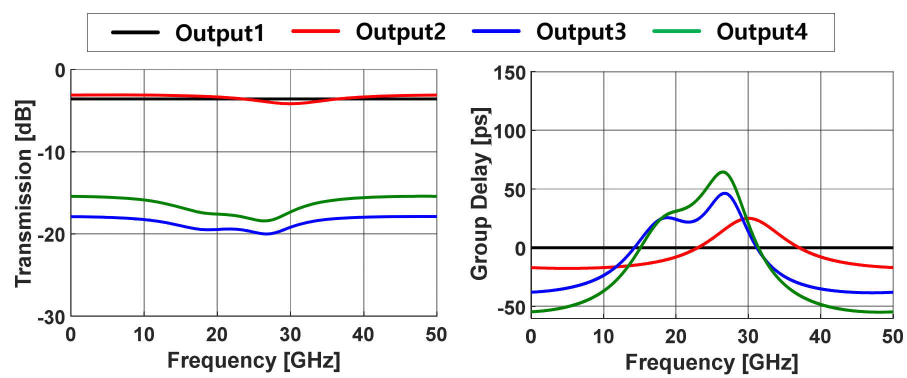


1. Output 1 & 2 Path Tuning

- Maximize monitor1 response while tuning MZI1&2
- Find critical coupling ratio of Ring1
- Find critical coupling ratio of Ring2
  - Set Ring1 to zero coupling
- Tune Ring1&2 MZI couplers to designed value
  - Using MZI characteristic and critical coupling ratio
- Tune MZI2 coupling to equalize output power
  - Using MZI characteristic and maximum coupling ratio



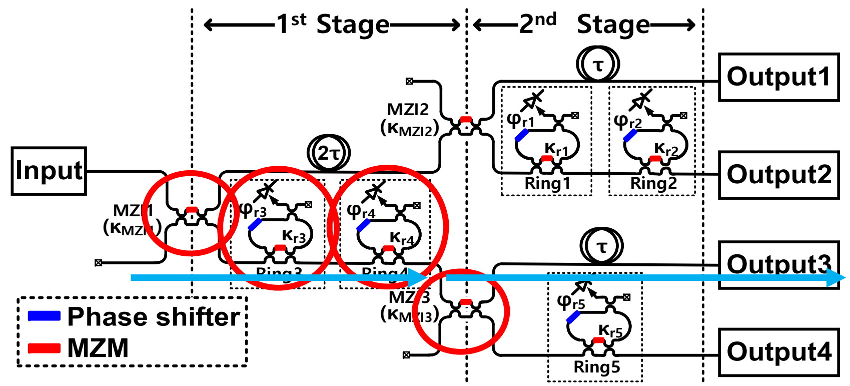
After Step1

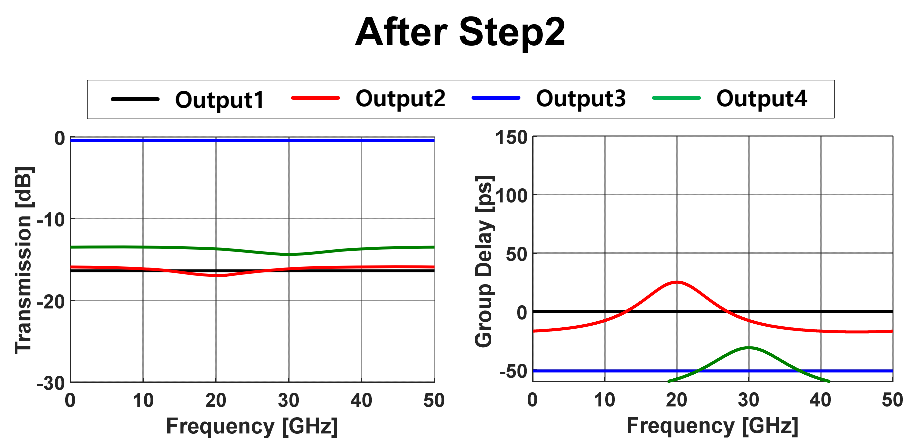


- Outputs 1 & 2 are now close to desired group delay at 30GHz and have near equal power, while Outputs 3 & 4 are still highly distorted

2. Output 3 Path Tuning

- Maximize monitor3 response while tuning MZI1
- Find critical coupling ratio of Ring3
- Find critical coupling ratio of Ring4
  - Set Ring3 MZI coupler to zero coupling
- Tune Ring4 MZI coupler to zero coupling
  - Using MZI characteristic and critical coupling ratio
  - Tune to zero for Ring5 coupling tuning in Step3

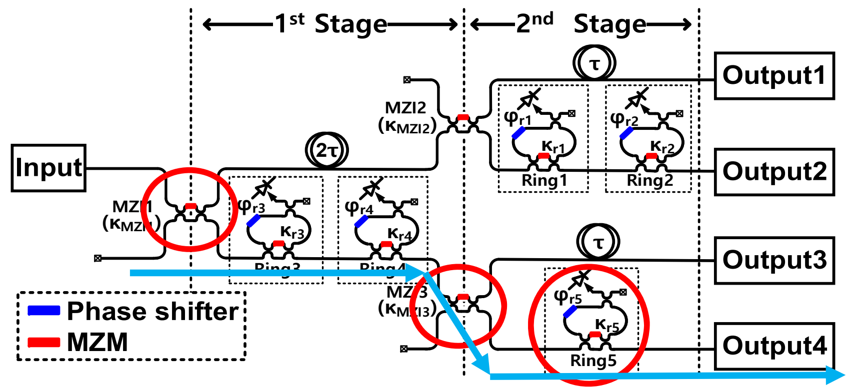




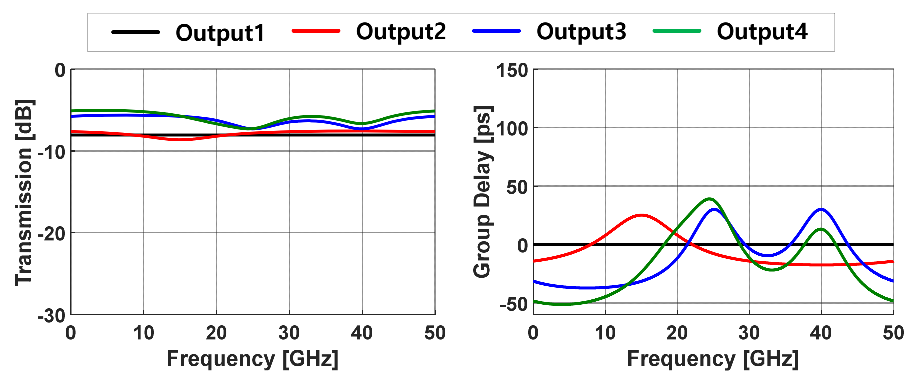
- After this intermediate step, the Output 3 group delay response is flat due to both Rings 3 & 4 coupling ratio being set to zero in preparation for the next step

3. Output 4 Path Tuning

- Maximize monitor5 response while tuning MZI3
- Find critical coupling ratio of Ring5
- Tune Ring3,4&5 MZI couplers to designed value
  - Using MZI characteristic and critical coupling ratio
- Tune MZI1&3 coupling to equalize output powers
  - Using MZI characteristic and maximum coupling ratio



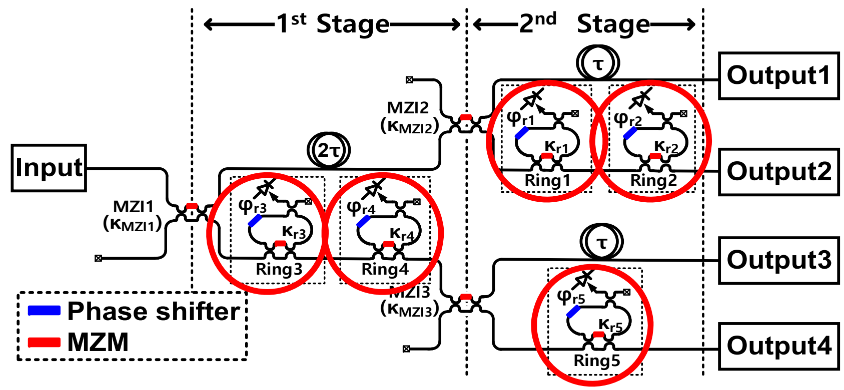
After Step3



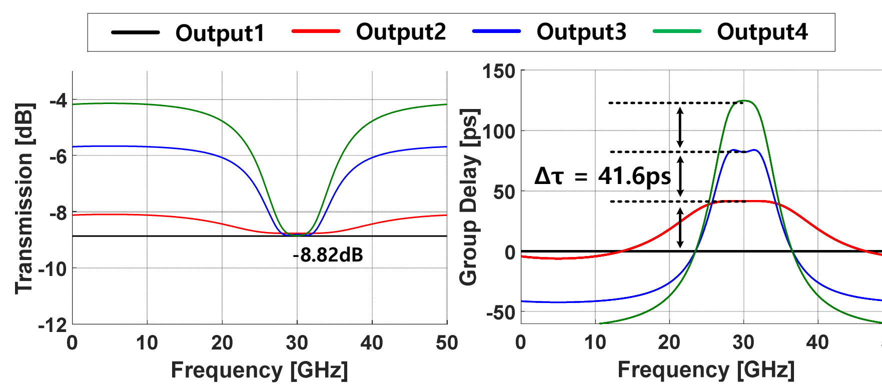
- The 4 channel output powers are now closer, but group delays are still off due to the ring's resonance frequencies not being set

4. Resonance Tuning

- Resonance tune Ring1-5 to maximize the corresponding monitor reading
- Multiple iterative tuning to compensate thermal cross-talk
- Input laser frequencies are switched to center frequencies of each ring for targeted angle

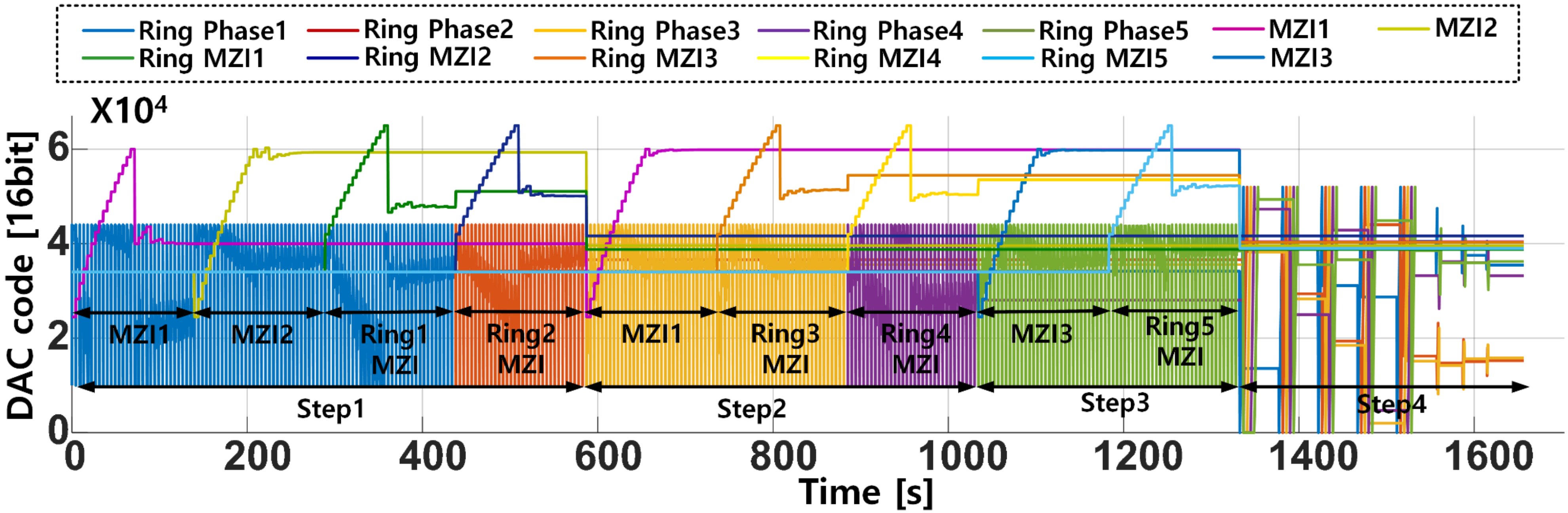


After Step4



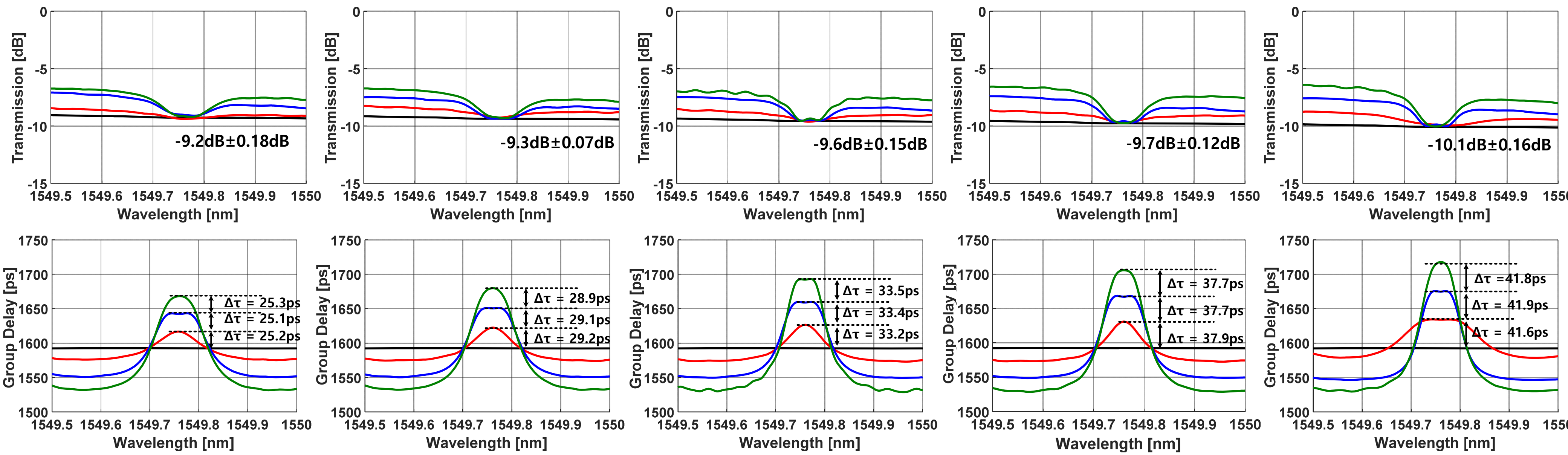
- The 4 channel outputs now have well-defined group delay responses and equalized power around the 30GHz center frequency

Measured Tuning Convergence



- Involves tuning 13 heaters
- While ORR MZI tuning, corresponding ring phase shifters are tuned in parallel
- Total tuning time 1617s

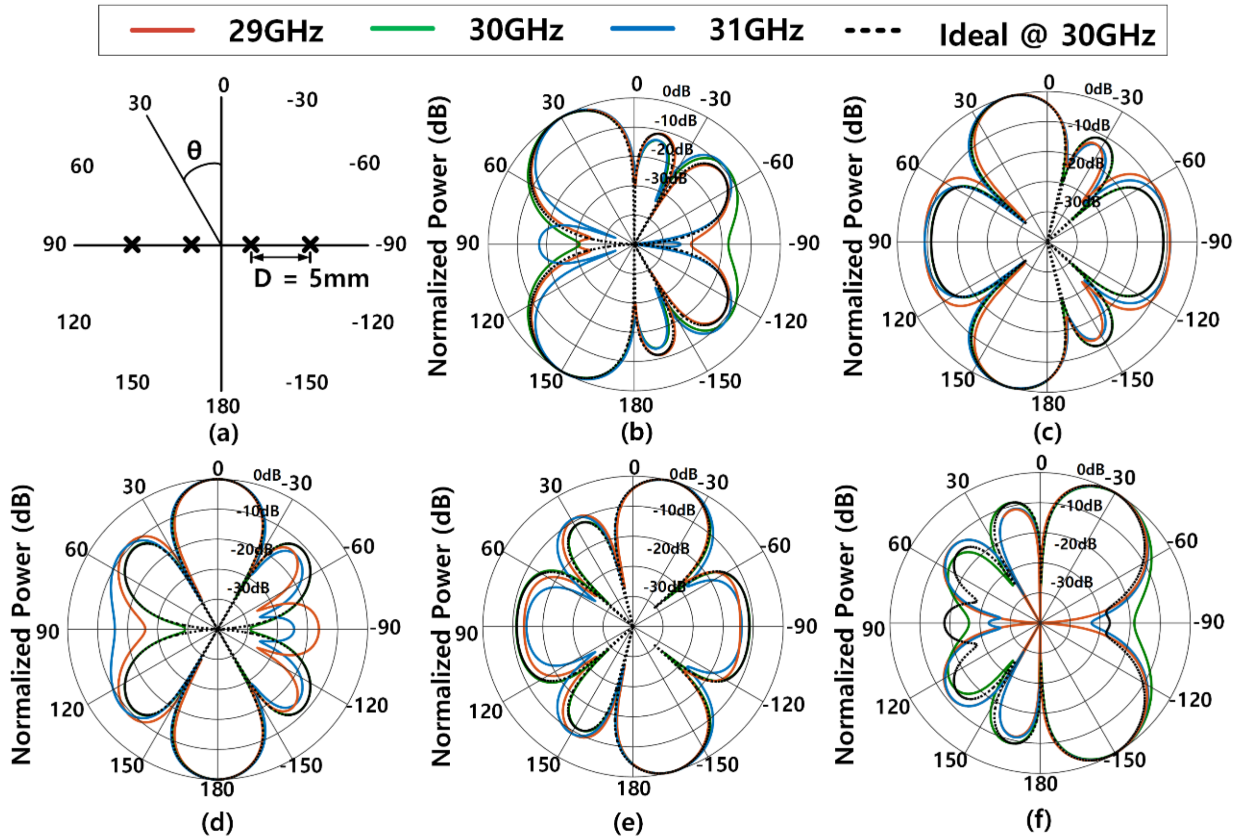
Measured OBFN Results



θ=150° θ=165° θ=180° θ=195° θ=210°

- Initial OBFN response is calibrated to have >2GHz bandwidth, centered at 30GHz relative to the 1550nm laser frequency
- Tuned result shows errors less than 0.3ps (OVNA resolution limit is 0.2ps)
- Each output showed power difference <0.2 dB mainly due to the grating coupler fabrication variations and alignment error

Beam Pattern Simulation Results



- 4-element linear antenna array with 5mm spacing beam patterns simulated based on measured OBFN responses
- Good directionality is achieved with main lobe showing at least 9.5dB larger gain than side lobes
- True time-delay operation of the ORRs allows for squint-free operation over 29-31GHz

Conclusion

- Automatic monitor-based calibration schemes developed for ORR-based photonic integrated circuits
- Severely degraded initial responses and reconfiguration demonstrated for $2^{nd}/4^{th}$-order APF-based pole/zero filters and a 1X4 asymmetric binary tree OBFN
- Leveraging the proposed calibration schemes can allow for robust operation of these photonic structures in future wideband communication systems

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Automatic Monitor-Based Tuning of APF-Based Pole/Zero Filters

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- G. Choo, S. Cai, B. Wang, C. Madsen, K. Entesari, and S. Palermo, "Automatic Monitor-Based Tuning of Reconfigurable Silicon Photonic 2nd-Order APF-Based Pole/Zero Filters," *OSA Conference on Lasers and Electro-Optics*, May 2017.
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- G. Choo, C. Madsen, S. Palermo, and K. Entesari, "Automatic Monitor-Based Tuning of RF Silicon Photonic True-Time-Delay Beamforming Networks," *IEEE International Microwave Symposium*, June 2018.
- G. Choo, C. Madsen, S. Palermo, and K. Entesari, "Automatic Monitor-Based Tuning of a Silicon Photonic 1X4 Asymmetric Binary Tree True-Time-Delay Beamforming Network," *IEEE-OSA Journal of Lightwave Technology*, vol. 36, no. 22, pp. 5263-5275, Nov. 15, 2018.